GEOPHYSICS

VOL. XXIII, NO. 3 JULY, 1958

Attenuation of Shear and Compressional Waves in Pierre Shale ..... *F. J. McDonal, F. A. Angona, R. L. Mills, R. L. Sengbush, R. G. Van Nostrand, and J. E. White* 421

Elimination of Secondary Pressure Pulses in Offshore Exploration (A Model Study) ..... *William C. Knudsen* 440

An Experimental Investigation of Factors Affecting Elastic Wave Velocities in Porous Media ..... *M. R. J. Wyllie, A. R. Gregory, and G. H. F. Gardner* 459

Sound Velocity vs. Temperature in Water-Saturated Sediments ..... *George Shumway* 494

Maximum Gravity Effect of Certain Solids of Revolution ..... *Leslie Duska* 506

Results for a Gravity Control Network at Airports in the United States ..... *G. P. Woollard* 520

Numerical Resistivity Analysis: Horizontal Layers ..... *Keeva Vozoff* 536

Some Technical Aspects of Reflection Seismic Prospecting in the Sahara .. *M. Pieuchot and H. Richard* 557

Case History of the Sojourner Oil Field, Haskell County, Texas, a Geochemical Confirmation ..... *W. R. Ransone* 574

DEPARTMENTS

Patents 579

Reviews and Publications Received 588

Memorial
William Palmer Lawrence ..... *W. T. Born* 594

Erratum
Henry Cornelius Cortes Memorial 595

Contributors 596

Society Round Table
Committees 602
Local Sections 603
Membership Applications Received 605
Prize Essay—A Gravity Investigation of a Sulphide Deposit ..... *Joseph F. Goetz* 606
11th Annual Midwestern Exploration Meeting 624
Announcements 633
Personal Items 635

Calendar of Meetings 638

Published by the

Society of Exploration Geophysicists

FOR SEISMIC EXPLORATION

NATIONAL GEOPHYSICAL CO., INC.
8800 Lemmon Avenue
Dallas, Texas

DALLAS
DENVER
HOUSTON
MIDLAND
SHREVEPORT
•
CALGARY

NATIONAL GEOPHYSICAL CO. OF CANADA, LTD.
Calgary, Alberta, Canada

for international surveys contact

namco INTERNATIONAL INCORPORATED
P. O. Box 13127, Dallas, Texas
Phone Fleetwood 2-2671

GEOPHYSICS

Published by the Society of Exploration Geophysicists

LAWRENCE Y. FAUST — 1957-1959 Editor

Amerada Petroleum Corp., Box 2040, Tulsa 2, Okla.

ASSOCIATE EDITORS (1957-1959)

G. E. ARCHIE — Well Logging
Shell Oil Co., Box 2099, Houston 1, Texas

MILTON B. DOBRIN — Experimental Seismology
Triad Oil Co., Ltd., 535 7th Avenue W., Calgary, Alberta, Canada

JOHN C. HOLLISTER — Mining Geophysics
Department of Geophysics, Colorado of Mines, Golden, Colorado

PAUL L. LYONS — Seismic Theory
Sinclair Oil and Gas Co., Box 521, Tulsa 2, Okla.

L. L. NETTLETON — Gravity and Magnetic Prospecting
Gravity Meter Exploration Co., 340 M. Esperson Building, Houston 2, Texas

O. F. RITZMANN — Patents
The Gulf Companies, Gulf Building, Pittsburgh 30, Pennsylvania

IRWIN ROMAN — Electrical Prospecting
Geophysics Branch, U.S. Geological Survey, Washington 25, D.C.

EDGAR J. STULKEN — Seismic Field Techniques and Operations
Geophysical Service Inc., 100 Exchange Park North, Dallas 35, Texas

Manuscripts of papers submitted for publication in GEOPHYSICS should be sent directly to the Editor, with the exceptions noted below.

Reviews of geophysical literature published outside of this journal should be sent to the Chairman of the Reviews Committee.

Announcements, news items, and personal items should be sent to the business manager (see next page).

Form of Manuscript and instructions for its preparation may be found in GEOPHYSICS, v. 19, p. 141-153. Reprints of this style guide may be obtained from the business manager (see next page) upon request.

Responsibility for all statements and opinions made in GEOPHYSICS must be assumed by the repective authors.

Discussions and Letters to the Editor are welcomed by the Editor.

Subscriptions are given to all members of the Society in good standing as part payment for their dues. For non-members and organizations the subscription rate is $10.00 per year in the United States and its possessions and $10.50 per year in all other countries.

Change of Address Notice should be sent to the Business Manager (see next page). Claims for non-receipt must be sent within 3 months of date of publication to be filled gratis.

Single Copy price is $2.50 to members and $3.00 to non-members. For foreign shipment add 20¢ per copy. Subscriptions and single copy orders should be sent to the business manager (see next page).

Microcard copies of all back issues of GEOPHYSICS are available through the business office—prices upon request.

Advertising rates will be furnished by the Business Manager upon request. No advertisements will be accepted for prospecting methods based on hypotheses which are at variance with the accepted principles of physics.

Permission to Copy text material from GEOPHYSICS is limited to one page and is granted on the express condition that reference be made to the source of the material. Larger text excerpts and illustrations from GEOPHYSICS may not be reproduced without written permission of the Editor.

Indexed regularly by Engineering Index, Inc. and by The Applied Science and Technology Index.

Published by George Banta Company, Inc., Menasha, Wisconsin. Issued five times a year in January, April, July, October and December. Entered as second class matter September 7, 1938 at the post office at Menasha, Wisconsin, under the Act of March 3, 1879. Acceptance for mailing at the special rate of postage provided for in the Act of February 28, 1925, embodied in paragraph 4, Section 538, P. L. & R., authorized March 19, 1941. Copyright 1958 by the Society of Exploration Geophysicists.

MODERN

Society of Exploration Geophysicists

The *Society of Exploration Geophysicists* had its beginning in 1930 when it was organized in Houston, Texas as the *Society of Petroleum Geophysicists*, the name being changed to its present form in 1936. The Society is dedicated to the advance of the science of geophysics and the art of geophysical prospecting. Through its journal GEOPHYSICS it supplies a medium for the dissemination of new knowledge in the field.

BUSINESS OFFICE

COLIN CAMPBELL, *Business Manager*
H. L. FARRIS, *Editorial Assistant*
Box 1536, Tulsa 1, Oklahoma

COUNCIL

OFFICERS (1957-1958)

O. C. CLIFFORD, JR. — *President*
The Atlantic Refining Co., Box 2819, Dallas 21, Texas

BEN F. RUMMERFIELD — *Vice-President*
Century Geophysical Corp., Jenkins Building, Tulsa 3, Oklahoma

HOWARD E. ITTEN — *Secretary-Treasurer*
Empire Geophysical, Inc., 6000 Camp Bowie Boulevard, Fort Worth, Texas

LAWRENCE Y. FAUST — *Editor*
Amerada Petroleum Corp., Box 2040, Tulsa 2, Oklahoma

ROY F. BENNETT — *Past President*
Sohio Petroleum Co., Skirvin Tower, Oklahoma City, Oklahoma

R. C. DUNLAP, JR. — *Prior Past President*
Geophysical Service Inc., 100 Exchange Park North, Dallas 35, Texas

DISTRICT REPRESENTATIVES

Ark-La-Tex Geophysical Society
Jackson S. Young (1958)
Herbert J. Ferber (1959)

Canadian Society of Exploration Geophysicists
F. A. Hale (1958)
P. I. Bediz (1959)
Harry McGrew (1959)

Casper Geophysical Society
W. H. Hawkes (1959)

Dallas Geophysical Society
Martin C. Kelsey (1958)
Glen M. Conklin (1959)
Paul E. Nash (1959)

Denver Geophysical Society
A. Haig (1958)
Leslie C. Spenser (1959)

Fort Worth Geophysical Society
H. E. Itten (1958)
A. E. McKay (1959)

Houston Geophysical Society
Richard H. Parker (1958)
J. E. McGee (1959)
W. H. Taylor (1959)

Jackson Geophysical Society
John D. Moredock (1958)

Montana Geophysical Society
R. E. Whitmore (1959)

New Mexico Geophysical Society
F. A. Grimm (1959)

Geophysical Society of Oklahoma City
Richard M. Davis (1958)

Pacific Coast Section, SEG
Robert E. Plumb (1958)
James A. Kurfess (1958)
E. M. Curry (1959)

Permian Basin Geophysical Society
Lorenz Shock (1958)
C. N. Page (1958)
G. A. Grimm (1959)

Geophysical Society of South Texas
W. Lee Moore, Jr. (1959)

Southeastern Geophysical Society
L. W. Cobena (1958)
Edwin A. Malone (1959)

Southwest Louisiana Geophysical Society
E. L. Ricketts (1959)

Geophysical Society of Tulsa
J. M. Crawford (1958)
W. M. Erdahl (1959)
Paul L. Lyons (1959)

Utah Geophysical Society
R. J. Lacy (1959)

Please mention GEOPHYSICS when answering advertisers

MODERN ALTIMETER SURVEYS

AMERICAN PAULIN SYSTEM

MICRO SURVEYING ALTIMETER

Intervals as close as ONE FOOT

Models available in all ranges.

ENGLISH or METRIC.

Designed for rugged field use under all climatic conditions.

Price in U.S.A.
MICRO MODELS $300
TERRA MODELS $250

FIELD INSTRUMENT

WRITE FOR DESCRIPTIVE CATALOG

BETTER ALTIMETER SURVEYS AT LOWER COST

MICRO SURVEYING BAROGRAPH

- CHART READING IMMEDIATELY AVAILABLE
- ACCURATE, SENSITIVE, (Same as our Micro Altimeter)
- EASILY READ
- DEPENDABLE
- LIGHT WEIGHT — EASILY PORTABLE

PRICE IN U.S.A.: $790 complete READY FOR USE

MADE IN U.S.A.

BASE INSTRUMENT RECORDER

MODEL SMB-5

PRECISION RECORDER REPLACES BASE OPERATOR

AMERICAN PAULIN SYSTEM

1524 SOUTH FLOWER STREET • LOS ANGELES 15, CALIFORNIA, U.S.A.

THE WORLD'S LEADING MANUFACTURER OF SURVEYING ALTIMETERS

NOW a Cone-Type Rock Bit is included in the HAWTHORNE "*Blue Demon*" LINE!

a COMPLETE LINE of bits for all soft-medium-hard formation drilling

A Cone-Type Rock Bit . . . for Oil and Minerals Exploration and Quarry Blast Hole Drilling . . . is now included in the Hawthorne "Blue Demon" *All-Formation* drill bit line.

Designed for drilling harder formations than are regularly recommended with the patented "Blue Demon" Replaceable Blade Bits, the Cone-Type Rock Bit is available from authorized Hawthorne dealers in 3⅞", 4¼", 4½", 4¾" and 5⅝" sizes.

Consistently priced, wherever you go, ask for Hawthorne Bits for all your drilling requirements.

WRITE FOR ILLUSTRATED CATALOG

HERB J. HAWTHORNE INC.

P. O. Box 7366 • Houston 8, Texas • Cable Address: HAWBIT

NOW OPERATING!
Century's
Seismic Data Reduction Center

The Oil Industry's FIRST General Contract Seismic Reduction Service

What Century's SEISMIC Data Reduction Service Means To You . . .

- A cross section of seismic records corrected without distortion for normal move-out, weathering and elevation differences.
- The ability to work heretofore "no record" areas by improving signal-to-noise ratio through compositing and/or filter discrimination.
- A means of analyzing subsurface stratigraphic and lithologic conditions.
- More discrimination and integration in your oil finding efforts.
- A clearer and more comprehensive presentation of seismic data to administrators and geologists who are not geophysicists.

For Full Information Phone

CHerry 2-8121
TULSA, OKLAHOMA

AMhurst 9-5571
CALGARY, ALBERTA

CENTURY GEOPHYSICAL CORPORATION
JENKINS BUILDING TULSA, OKLAHOMA

CENTURY GEOPHYSICAL CORPORATION OF CANADA
1105 7th AVENUE WEST, CALGARY, ALBERTA, CANADA

Where nature never smiles
Du Pont seismic products

Loading "Nitramon" S in the desert. "Nitramon" S and its primers are packed in threaded metal cans that are virtually weatherproof. Charges are easily assembled and so rigid that they can often be loaded when gelatin dynamite can not.

make her talk

AROUND THE GLOBE, seismic crews come to grips with nature in the raw.

Heat, moisture, cold, difficult terrain, and unskilled help often create special problems for both men and explosives. That's why so many crews prefer the extra advantages of these Du Pont products for seismic exploration:

"NITRAMON" S, safest blasting agent known, can't be detonated by flame, shock, ordinary blasting caps, or even a .30 caliber bullet! Yet its high power won't deteriorate even after months of storage in any weather; and it's water resistant—ideal for deep holes.

"NITRAMON" WW, compares to "Nitramon" S, but is especially designed for offshore work. Watertight metal cans make it immune to heat, rain, sea spray. Cans always sink, but are easily buoyed up.

SEISMOGRAPH 60% "HI-VELOCITY" GELATIN stores extremely well and will deliver results even under the worst operating conditions. Available with Du Pont Fast-Coupler, quickest way to assemble charges.

"SEISMEX" PW, packed in rugged seismograph-type shells, is low-cost dynamite for shallow hole or surface pattern work.

"SSS" ELECTRIC BLASTING CAP, so dependable it outsells its nearest competitor two to one; gives unexcelled storage and performance in any climate or conditions. Important safety advantage: these caps are highly static resistant.

For more information on Seismic products for domestic or foreign work, call your Du Pont representative or write: E. I. du Pont de Nemours & Co. (Inc.), Explosives Department, Wilmington 98, Delaware.

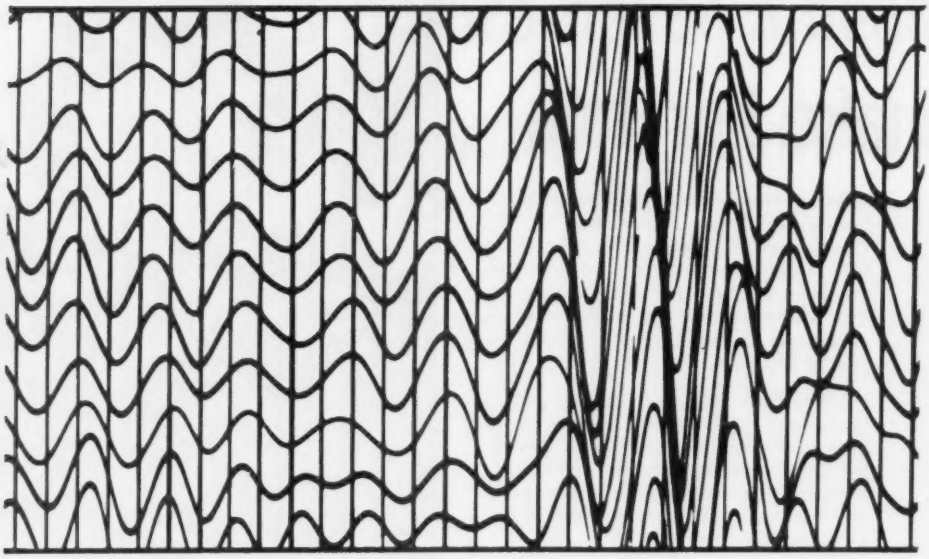
DU PONT
REG. U.S. PAT. OFF.

Better Things for Better Living . . . *Through Chemistry*

DU PONT SEISMIC PRODUCTS

"Nitramon" S storage. In steamy tropical jungles and in bone-chilling arctic zones, "Nitramon" S and primers have been stored for many months with no sign of deterioration.

Oil exploration in Pakistan brings crew into rugged country which demands the most from the men and their Du Pont seismic products.



Get perfect recordings of every shot with Seismo-Writ

Here's why Du Pont Seismo-Writ is better in these four ways.

SPEED. Seismo-Writ can be *processed* quicker. Even if extreme underexposure forces over-development, you still get a good, clear, easy-to-read trace. You can process Seismo-Writ in developer temperatures up to 125°F.

STABILITY. Seismo-Writ has minimum curl and won't crack. It's easy to handle, roll and store. It won't soften, even under toughest field conditions.

CLARITY. Seismo-Writ is free from stain and fog. You get highest density, both in timing lines and in reflection traces.

SAFETY. Seismo-Writ is wrapped in a heat-sealed, moisture-proof inner pouch and packaged in a durable waterproof canister. This package assures maximum protection—even if dropped into water, it will float, and its bright red color makes for easy spotting and recovery.

E. I. du Pont de Nemours & Co. (Inc.)
Photo Products Department
Nemours 2420-17, Wilmington 98, Del Ge-7

Please send me your booklet, "Seismo-Writ Photorecording Paper"

Name _____

Firm _____

Street _____

City _____ State _____

DU PONT
REG. U. S. PAT. OFF.

Better Things for Better Living . . . *through Chemistry*

PROGRESSIVE MANAGEMENT

WORLD WIDE OPERATIONS

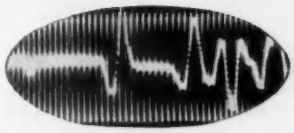
INTEGRATED SERVICE

SPECIALLY TRAINED PERSONNEL

FINEST MODERN EQUIPMENT

SCIENTIFIC DATA PROCESSING

ADVANCED RESEARCH



MAKING THE MOST OF GEOPHYSICAL DATA

UNITED GEOPHYSICAL

THE SHIELD KNOWN ROUND THE WORLD

UNITED'S SHIELD—SYMBOLIC of the reliability and integrity of its geophysical surveys and data interpretation—is a familiar emblem all around the world, wherever surveys are made. This black and yellow trademark signifies UNITED'S progressive service to the oil industry. It indicates UNITED'S INTEGRATED SERVICE of Continuous Advanced Research, Specially Trained Personnel, World Wide Operations, Scientific Data Processing, Finest Modern Equipment and Progressive Management. For reliable geophysical surveys—represented by the familiar black and yellow UNITED shield—use UNITED'S INTEGRATED SERVICE.

UNITED GEOPHYSICAL CORPORATION

BOX M, PASADENA, CALIFORNIA

Seismograph • Gravimeter • Magnetometer

PASADENA, CALIFORNIA, 1200 South Marengo Avenue • CARACAS, VENEZUELA, S. A., Apartado 1085
HOUSTON, TEXAS, 1430 N. Rice Avenue, (Bellaire) • RIO DE JANEIRO, BRASIL, S. A., Rua Uruguiana 118,9° Andar
CALGARY, ALBERTA, CANADA, 531 8th Avenue, West • PARIS, FRANCE, 194 rue de Rivoli

Mr. Foreign Exploration Manager

Anywhere, this World

Let our Foreign Department explain to you how G.I., Inc. Weight Dropping Seismic Survey can save you *many dollars and secure useable information* in multi-hole shooting areas (*No drilling costs or explosives*). Proven by 2½ years of work in *difficult record areas.*

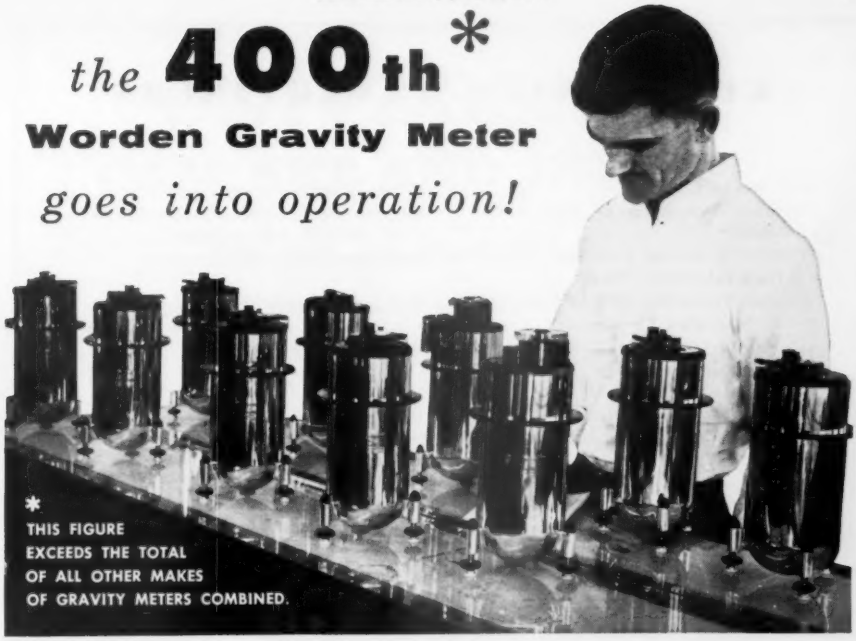
Geophysical Integrators Inc.

San Angelo, Texas

Box 887 **Phone 21821**

P.S. Weight Dropping Seismic Surveys can also save you money in single hole areas (*Less personnel and more miles of line per month*).

the 400th* Worden Gravity Meter *goes into operation!*



Texas Instruments Incorporated is the first and only member of a highly exclusive "400 Club." In the brief span since 1946, 400 compact and dependable Worden Gravity Meters have been precision-manufactured for use in widely varying world-wide services.

In virtually every conceivable operating condition, Wordens have proved their superiority in accuracy, portability, and trouble-free operation. Atop Mount Godwin Austen in Pakistan, in Europe's natural caves, in mine shafts of four continents, on the Greenland Ice Cap, during the IGY in Antarctica, from helicopter, horseback or jeep, from latitudes 0 to 90° . . . both geodetic and exploration Worden Gravity Meters have provided highly valuable information.

The Worden Gravity Meter weighs only five pounds—1/4 to 1/5 the weight of other gravity meters in use. The elastic system of the meter is quartz with basic mass of only five milligrams, and is sealed in a partial vacuum. Internally compensated, no external power source or heating coils are required for operation in any temperature. The Worden Meter does not require pampering or clamping between stations and will maintain its high accuracy under the roughest of expected operating conditions.

For further information on Worden Standard and Geodetic Gravity Meters, write for Bulletin No. GM-204.

TEXAS INSTRUMENTS INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB
Formerly: HOUSTON TECHNICAL LABORATORIES

7279

GEOPHYSICS ADVERTISERS

Aero Service Corporation 57
American Association of Petroleum Geologists 30
American Cyanamid Company 43
American Institute of Physics 24
American Paulin System 3
Arnold Magnetics Corporation 35
Askania-Werke 51
Atlas Powder Company 15

Thomas J. Bevan 74
Brailsford and Company, Incorporated 36

Century Geophysical Corporation 5
Continental Geophysical Company ... 61
Crossland Licensing Corporation Ltd. . 70
Custom Fabrication Corporation 26

Bert & Ralph Duesing 36
DuPont Explosives .....6 & 7
DuPont Photo Products 8

Eastman Kodak Company 25
Economic Geology 26
Elder Trailer and Body, Incorporated 23
Electrodynamic Instrument Corporation 34
Electro-Technical Labs. 13, 60
European Association of Exploration Geophysicists 38

Fairchild Aerial Surveys, Incorporated 32
Fortune Electronics, Incorporated ....*Insert after* 16

General Geophysical Company 31
Geophysical Associates International . .....*Insert after* 16
The Geophysical Directory 64
Geophysical Integrators Incorporated . 10
Geophysical Service Incorporated *4th cover*
W. & L. E. Gurley 47

Hall-Sears, Incorporated 68
Herb J. Hawthorne Incorporated 4
Hercules Powder Company 46

Independent Exploration Company ... 63

Klaus Exploration Company 41
Koenig Iron Works, Incorporated 29

Mayes-Bevan Company 37
Mayhew Supply Company, Incorporated 52
E. V. McCollum & Company 59
McCollum Exploration Company 39

National Geophysical Company, Incorporated .....*2nd cover*

Olsen Seismograph Supplies 26

Petty Geophysical Engineering Company 65
Porta-Kamp 69
Prakla 42

Robert H. Ray Company 55
Rayflex Exploration Company 27
Republic Exploration Company 45
Rogers Geophysical Companies 71
Ruska Instrument Corporation 58

Schlumberger Well Surveying Corporation 66
Seismic Engineering Company 28
Seismic Explorations Incorporated 53
Seismograph Service Corporation ....*3rd cover*
Seismos GmbH 72
Society of Exploration Geophysicists .. 14
Southwestern Industrial Electronics Company .....*Insert after* 26

Tex-Tube, Incorporated 56
Texas Instruments Incorporated *11, 40, 48, 67*
Texas Seismograph Company 24
Tidelands Exploration Company 33
Triad Transformer Corporation 73
Trija Publishing Company 54

United Geophysical Corporation 9

Varian Associates 62

Wallace & Tiernan Incorporated 50
Well Reconnaissance, Incorporated ... 49
Western Geophysical Company 16
World-Wide Instruments, Incorporated 44

Zeitschrift für Geophysik 54

Electro-Tech Adds Versatility with the . . .

UNIVERSAL
CAM SET AND INDEX

for use on their DS-7 Magnetic Tape Recorder And Playback Unit

- ✓ No need for separate cams for each area and spread set-up.
- ✓ Can be added to all existing DS-7 Units.

DS-7 Recorder and Playback Unit —

Purchase — $8750 with cam set

Rent — $550/mo. (with 90% of rental applying toward purchase, minimum rental four months)

Cam Index Mechanism — $375

Can be installed in field by user

Special Cam Sets — $250/set

One universal cam set plus index allows use with multiple combinations of velocity data and normal split-spread setups.

ELECTRO-TECH

ELECTRO-TECHNICAL LABS
DIVISION OF MANDREL INDUSTRIES
P. O. BOX 13243 HOUSTON 19, TEXAS

LEADERS IN THE FIELD OF SEISMIC INSTRUM

It Pays to Advertise

. . . in GEOPHYSICS

•

For information on rates and space requirements, write to

COLIN CAMPBELL
Business Manager

GEOPHYSICS
Box 1536
Tulsa 1, Oklahoma

GEOPHYSICS

•

Volume I 1936
Volume II 1937
Volume III 1938
Volume IV 1939
Volume V 1940
Volume VI 1941

BOUND IN BLACK BUCKRAM
LETTERED IN GOLD

Now Available
$6.00 Each

•

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536 Tulsa 1, Okla.

GEOPHYSICAL CASE HISTORIES, VOLUME II

Contents

General and historical papers 6
Salt dome case histories 6
Reef case histories 6
Anticline case histories 23
Stratigraphic trap case histories 3
Mining case histories 3
New uses case histories 5

Total number of papers 52

WITH GENERAL INDEX AND INDEX TO MAPS
$6.00 to SEG, AAPG and AIME members—$7.00 to others

Payment must accompany order No C.O.D. orders accepted

SOCIETY OF EXPLORATION GEOPHYSICISTS
Box 1536 Tulsa 1, Oklahoma

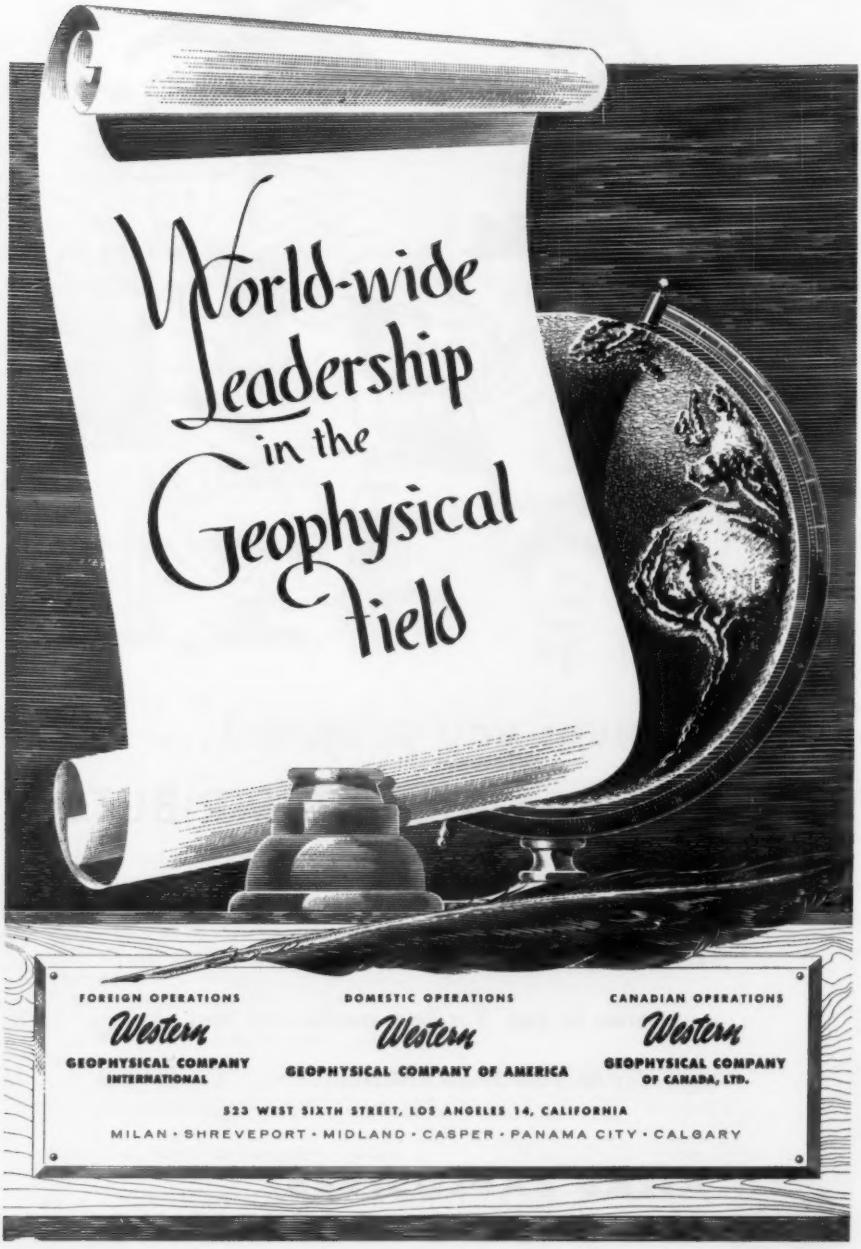
Wherever you prospect... you'll find an ATLAS DISTRIBUTOR

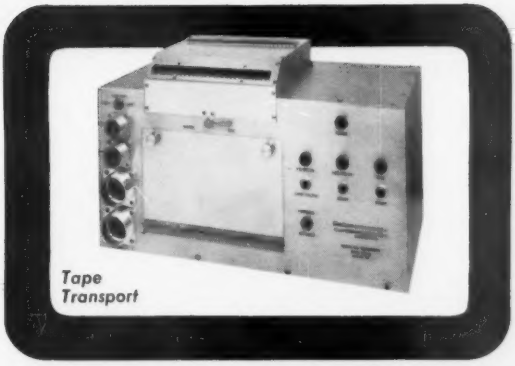
We look at it this way: If you can get there, we can get a full line of explosives, blasting agents and accessories to you. For best results and best readings, rely on your Atlas Distributor.

ATLAS EXPLOSIVES FOR SEISMIC PROSPECTING

Atlas Powder Company, Wilmington 99, Delaware

Please mention GEOPHYSICS when answering advertisers

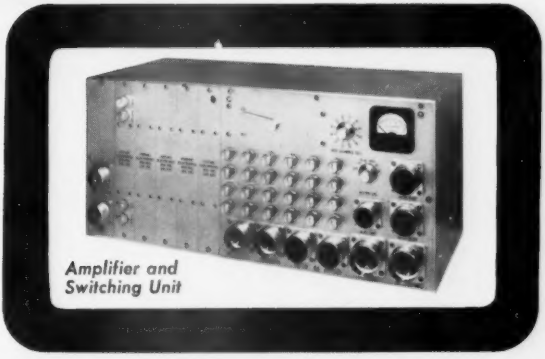

World-wide
Leadership
in the
Geophysical
field
FOREIGN OPERATIONS
Western
GEOPHYSICAL COMPANY
INTERNATIONAL
DOMESTIC OPERATIONS
Western
GEOPHYSICAL COMPANY OF AMERICA
CANADIAN OPERATIONS
Western
GEOPHYSICAL COMPANY
OF CANADA, LTD.
523 WEST SIXTH STREET, LOS ANGELES 14, CALIFORNIA
MILAN • SHREVEPORT • MIDLAND • CASPER • PANAMA CITY • CALGARY



Tape Transport

FORTUNE ELECTRONICS' SR-3 MAGNETIC TAPE RECORDER*

Most Practical Direct Recorder in the Field Today!



Amplifier and Switching Unit

Simple Design

The SR-3 has been especially designed to give outstanding performance under the most adverse field conditions. This rugged design demands that the instrument be free of non-essentials. An example of the SR-3's design simplicity is its *straight-forward,* adjustable headbank. Corrections are easily set and read, headbank cannot get out of calibration.

Completely Adaptable

No installation problems, interconnecting cables are all that is required to adapt the SR-3 to any existing system. With the SR-3 expensive re-wiring, and costly man-hours are eliminated, equipment out-of-production time is minimized.

Easily Serviced

A unique feature of the SR-3 is its uncomplicated construction. While this compact unit is made of sturdy, precision-made components, it is easily serviced by technicians familiar with seismic equipment. This feature helps to reduce shut-down time in the field due to equipment failure.

Superior Performance

The superior performance of the SR-3 more than meets the most exacting standards. Judge the performance characteristics of the SR-3 for yourself—write Fortune Electronics for complete physical and electrical specifications.

***Available on Fortune's lease-purchase plan**

Fortune Electronics, Inc.

H. H. HAPPEL—H. H. HAPPEL, JR.

2505 SOUTH BOULEVARD, HOUSTON, TEXAS

Represented in Dallas, Texas and Tulsa, Oklahoma by Indel Supply Company

Mirror

Data carefully obtained by GAI seismic surveys, followed by proper analysis, give you the facts upon which to base your decisions. If desired your exploration may be carried out with magnetic recording and section analysis. For a positive reflection of underlying geology, based on gravity, magnetic or seismic surveys anywhere in the world, you can depend on Geophysical Associates International, 3621 West Alabama, Houston 27, Texas, U.S.A.

gai

GMX

Dr. L. L. Nettleton
E. Joe Shimek
Dr. Nelson C. Steenland

VOLUME XXIII JULY, 1958 NUMBER 3

GEOPHYSICS

ATTENUATION OF SHEAR AND COMPRESSIONAL WAVES IN PIERRE SHALE*

F. J. McDONAL,† F. A. ANGONA,† R. L. MILLS,‡ R. L. SENGBUSH,† R. G. VAN NOSTRAND,§ AND J. E. WHITE¶

ABSTRACT

Attenuation measurements were made near Limon, Colorado, where the Pierre shale is unusually uniform from depths of less than 100 ft to approximately 4,000 ft. Particle velocity wave forms were measured at distances up to 750 ft from explosive and mechanical sources. Explosives gave a well-defined compressional pulse which was observed along vertical and horizontal travel paths. A weight dropped on the bottom of a borehole gave a horizontally-traveling shear wave with vertical particle motion. In each case, signals from three-component clusters of geophones rigidly clamped in boreholes were amplified by a calibrated, wide-band system and recorded oscillographically. The frequency content of each wave form was obtained by Fourier analysis, and attenuation as a function of frequency was computed from these spectra.

For vertically-traveling compressional waves, an average of 6 determinations over the frequency range of 50–450 cps gives $\alpha = 0.12$ f. For horizontally-traveling shear waves with vertical motion in the frequency range 20–125 cps, the results are expressed by $\alpha = 1.0$ f. In each case attenuation is expressed in decibels per 1,000 ft of travel and f is frequency in cps. These measurements indicate, therefore, that the Pierre shale does not behave as a visco-elastic material.

INTRODUCTION

The introduction of high-resolution seismic equipment, acoustic logging, seismic models, and the study of cores by high frequency acoustical methods has emphasized the need for a basic understanding of the propagation of sound through earth and seismic model materials. Even for the normal seismic band (20–100 cps) attenuation, and possibly dispersion, are important in unconsolidated materials. Attenuation of the higher frequencies is very evident in high-resolution recording and interval-velocity measurements. Furthermore, the common practice of applying high-frequency velocity determinations to the seismic band below 100 cps is inaccurate if dispersion is present.

Ricker (1953) has developed a theory of wavelet propagation based on the assumption of (1) an impulse as the initial displacement at the source and (2) a

* Presented at the 25th Annual Meeting of the Society at Denver on October 6, 1955. Manuscript received by Editor October 3, 1957.

† Magnolia Petroleum Company, Field Research Laboratory, Dallas, Texas.

‡ Summers and Mills, Inc., Dallas, Texas.

§ Société de Prospection et Exploitations Pétrolières en Alsace, Paris, France.

¶ Ohio Oil Company, Littleton, Colorado.

visco-elastic medium. This theory states that the breadth of a wavelet is proportional to the square root of the travel time of its center and that the amplitude of the particle velocity of the wavelet decreases as the five-halves power of travel time. This theory further states that, for the low frequency region of normal seismic work, attenuation is proportional to the square of frequency and velocity is constant. Above a specified transition frequency both the velocity of propagation and attenuation increase as the square root of frequency. Ricker (1953) also made an experimental study of the propagation of seismic wavelets in the Pierre shale near Limon, Colorado. No direct study of attenuation was made, but his measurements of wavelet breadth and wavelet amplitude are in reasonable agreement with his theoretical work.

Born (1941) conducted laboratory experiments with bars of shale, limestone, sandstone, and caprock, and he found that attenuation was proportional to the first power of frequency. The addition of small quantities of water, however, led to attenuation intermediate between the first and second powers of frequency. More recently, Collins and Lee (1956) have reported experiments in a quarry sandstone which indicate attenuation proportional to the first power of frequency, and they present theoretical considerations which indicate that the attenuation exponent may be arbitrarily close to unity without assuming a non-linear system. Knopoff (1956) has extended Zener's (1938, 1948) work on metals to earth materials, and suggested solid friction as a mechanism of attenuation. This leads to attenuation proportional to the first power of frequency and velocity independent of frequency.

ATTENUATION MEASUREMENTS

The measurements reported in this paper were undertaken to provide accurate data on attenuation of earth materials in place. Since the magnitude of attenuation in the normal seismic band is small, a thick section of uniform material is desirable. This requirement is met by the Pierre shale (Upper Cretaceous) in Eastern Colorado. In this area the Pierre shale is approximately 4,000 ft thick and exceptionally uniform. An acoustic velocity log of one of the test holes (Figure 1), however, does show minor variations in the interval between 250 and 800 ft. The largest break at 740 ft represents a reflection coefficient of only 0.04. Other variations do not exceed 0.03. On this basis multiple reflections should not produce significant interference. The observed velocity variations, however, are important for horizontal paths. Adjacent layers of slightly different velocities lead to the interference of overlapping signals. The result is an apparent increase in wavelet breadth and, in some cases, severely distorted wave forms.

Attenuation of vertically traveling compressional waves was determined from signals recorded by 5 detectors positioned in a cluster of boreholes (Figure 2) such that the detectors and source formed a straight line approximately vertical. Booster and one-pound charges were shot at depths of 250 to 300 ft. Detectors were placed at depths of 350, 450, 650, and 750 ft.

Since velocity measurements in these and adjacent boreholes indicated a uniform material, a correction for spherical spreading was made and attenuation was computed directly from a Fourier analysis of these signals. Typical records are shown in Figures 3 and 6. The corresponding Fourier analyses and attenuation values are shown in Figures 4, 5, 7, and 8. The average attenuation for 6

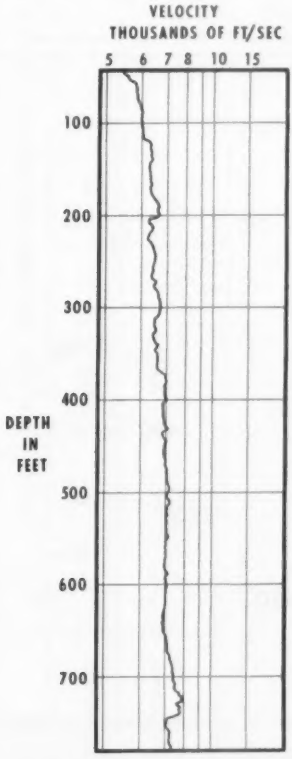


FIG. 1. Velocity log of test hole.

separate shots is given by Figure 9. The relation $\alpha = 0.12$ f fits the data in an acceptable manner, but the best fit of the data (by the least squares method) yields the expression, $\alpha = 0.065\ f^{1.1}$ where α is the attenuation in db per 1,000 ft, and f is the frequency in cps.

Unfortunately we were not able to generate satisfactory vertically traveling shear waves, but we did produce acceptable horizontally traveling shear waves by dropping a 200-lb weight on the bottom of a 500-ft borehole. Shear signals

were recorded by three component geophone clamps placed at this same depth in a line of boreholes at horizontal distances of 79, 142, 273, 321, 370, and 630 ft. Typical records for shear waves are shown in Figure 10. It is obvious from inspection that wavelet broadening and attenuation of the higher frequencies is much more pronounced than for compressional waves. Attenuation of shear waves is approximated by the relation $\alpha = 1.0$ f db per 1,000 ft (Figure 12).

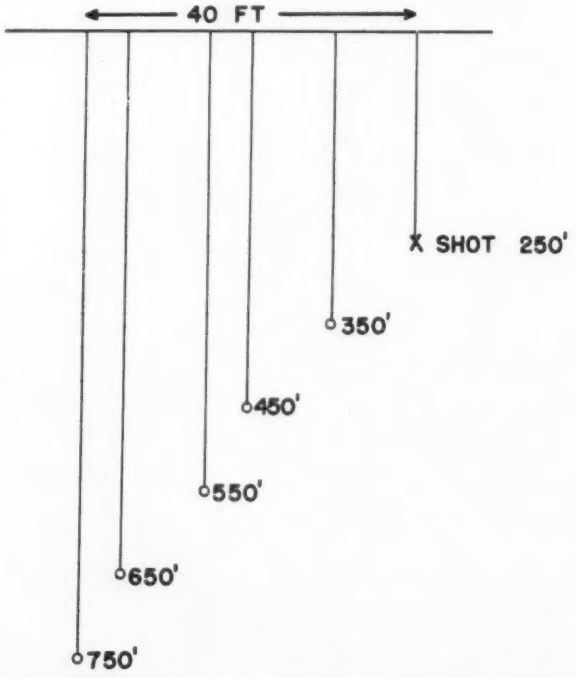


FIG. 2. Geometry employed for the study of vertically traveling compressional waves.

For vertical travel the average shear and compressional velocities were 2,630 and 7,100 ft/sec, respectively, for the depth interval of 450 to 550 ft. For horizontal travel at a depth of 500 ft the corresponding velocities were 2,680 and 7,360 ft/sec.

DISCUSSION OF RESULTS

The attenuation measurements reported in this paper disagree with the previous work of Ricker (1953) in several respects. Our measurements indicate that attenuation of vertically traveling compressional waves is proportional to the first power of frequency, the decay of wavelet amplitude as a function of travel

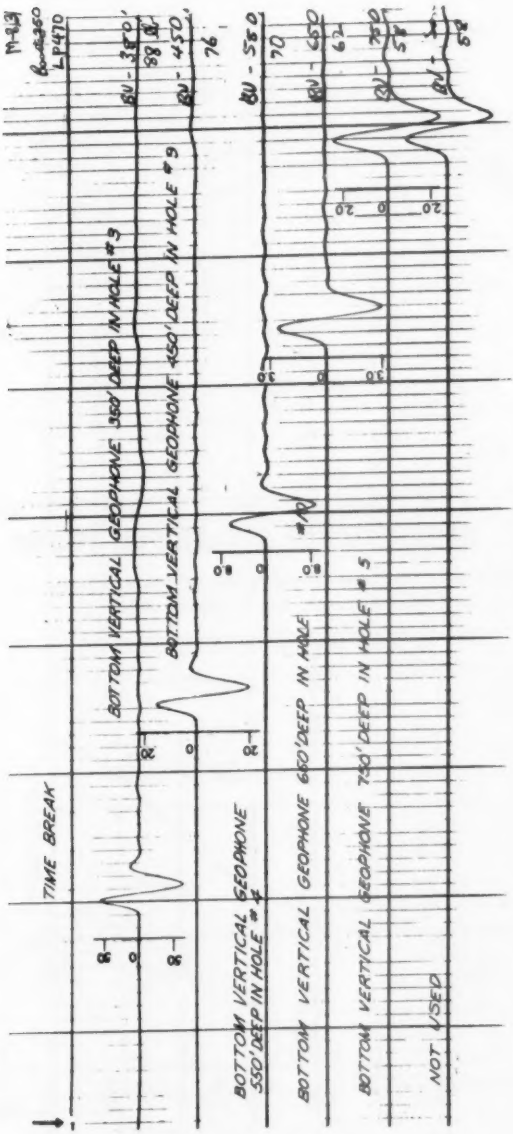

TIME BREAK
BOTTOM VERTICAL GEOPHONE 350' DEEP IN HOLE #9
BOTTOM VERTICAL GEOPHONE 450' DEEP IN HOLE #9
BOTTOM VERTICAL GEOPHONE 550' DEEP IN HOLE #5
BOTTOM VERTICAL GEOPHONE 660' DEEP IN HOLE
BOTTOM VERTICAL GEOPHONE 750' DEEP IN HOLE #5
NOT USED
BW - 350
BW - 450
BW - 550
BW - 660
BW - 750
BW - 850

FIG. 3. Vertically traveling compressional waves generated by a booster charge at a depth of 250 ft.
Record M. (Amplitudes are expressed in units of cm/sec$\times 10^{-3}$.)

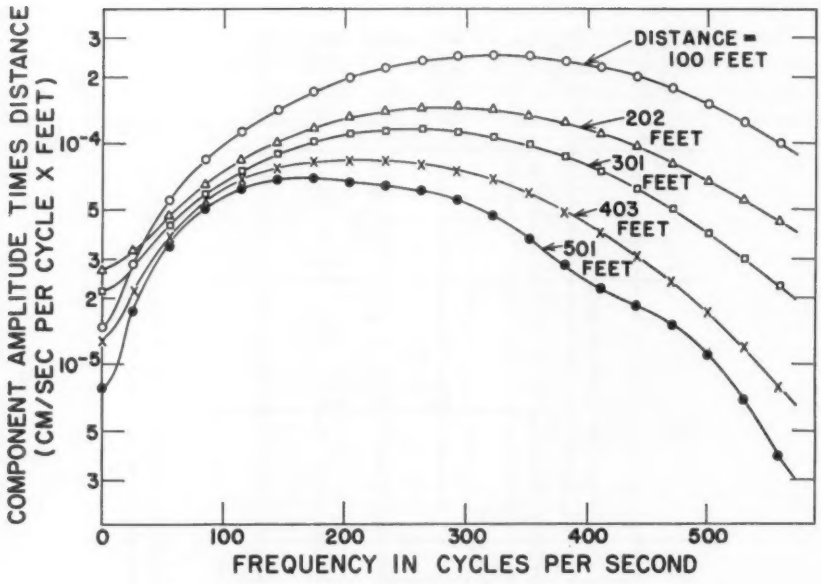


FIG. 4. Spectra of vertically traveling compressional waves generated by a booster charge at a depth of 250 ft. Record M.

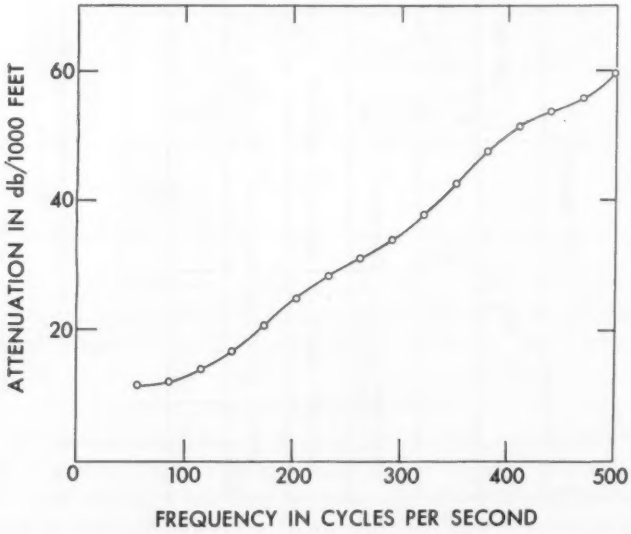


FIG. 5. Attenuation of vertically traveling compressional waves generated by a booster charge at a depth of 250 ft. Record M.

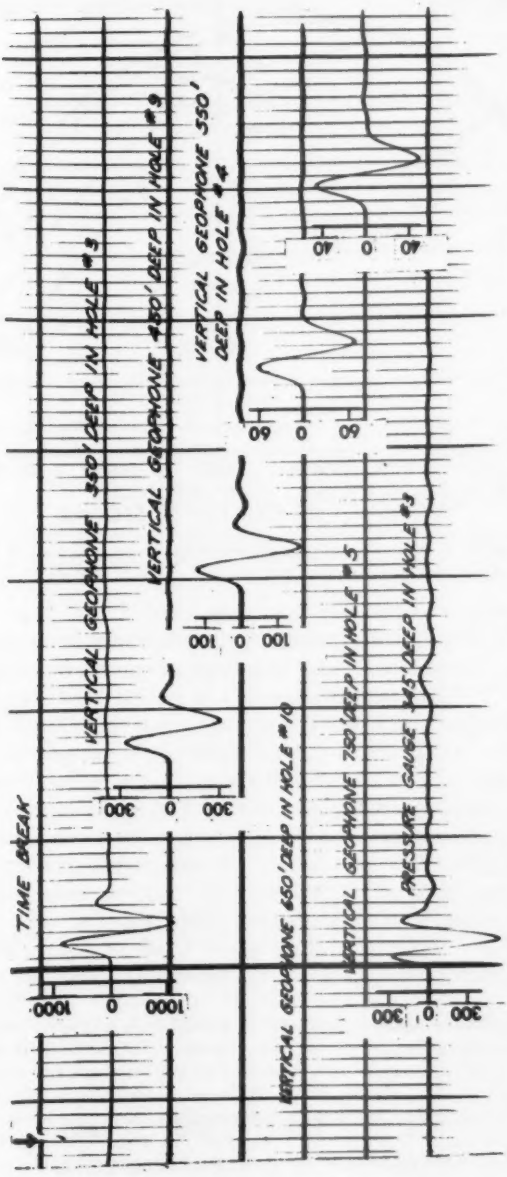


FIG. 6. Vertically traveling compressional waves generated by a charge of one pound of dynamite at a depth of 260 ft.
Record T. (Amplitudes are expressed in units of cm/sec$\times 10^{-3}$ and dynes/cm$^2\times 10^3$, respectively.)

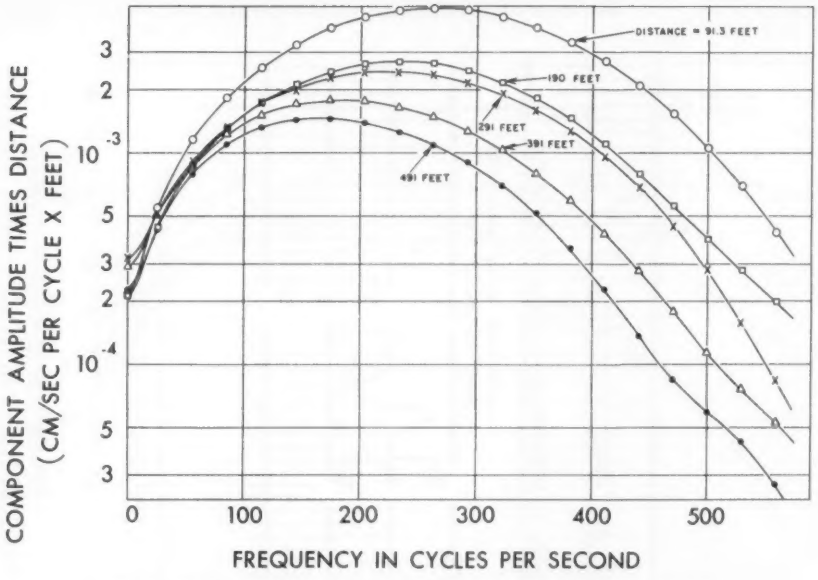


FIG. 7. Spectra of vertically traveling compressional waves generated by a charge of one pound of dynamite at a depth of 260 ft. Record T.

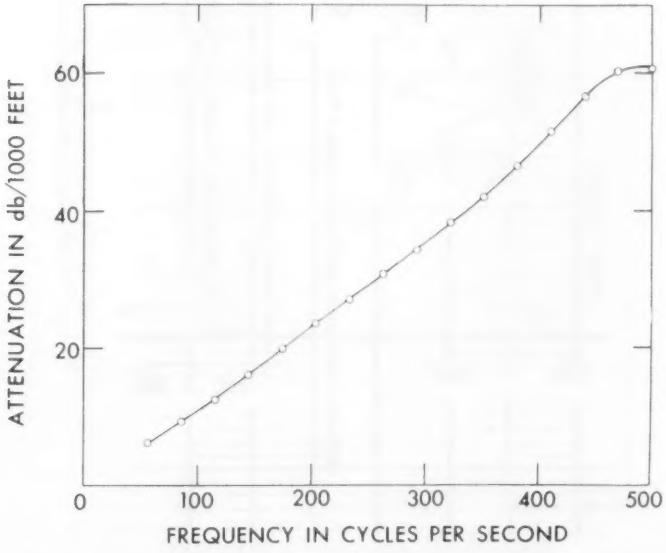


FIG. 8. Attenuation of vertically traveling compressional waves generated by a charge of one pound of dynamite at a depth of 260 ft. Record T.

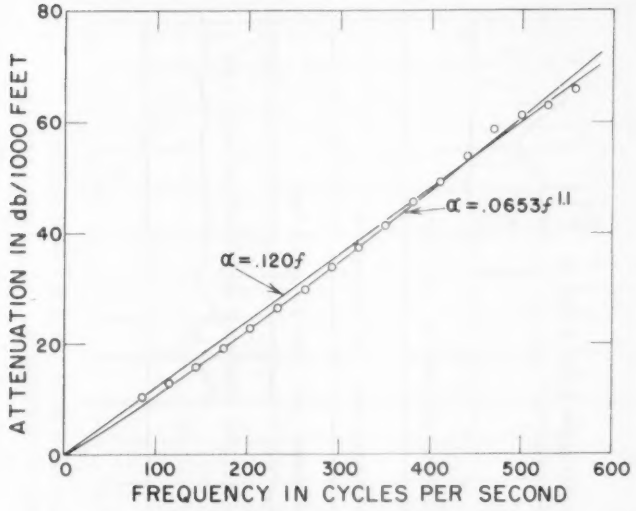


FIG. 9. Attenuation of vertically traveling compressional waves. This is the average attenuation for 6 records, including those of Figs. 5 and 8.

time is less rapid than Ricker's work indicates, and wavelet broadening is less.[1] The observed wave forms more nearly resemble a single cycle of a sine wave than they do Ricker wavelets. In summary, our measurements indicate that the Pierre shale does NOT behave as a visco-elastic material.

While unconsolidated material of the weathered zone may exhibit visco-elastic properties, the absence of dispersion further indicates that consolidated formations do not. Velocity determinations by acoustic velocity logs operating in the frequency range of 10 to 20 kc agree with geophone surveys to within a few percent. Since the two-receiver acoustic velocity log provides an absolute measurement of velocity determined by the distance and travel time between receivers, these measurements clearly indicate that no significant dispersion exists below 10 kc. For example, thick sections of Pennsylvanian shales and sands in Oklahoma (Magnolia No. 1 Bessie Weaver, McClain Co., Oklahoma), Gulf Coast sands and shales (Magnolia No. A-1X Louisiana State Lease 2922), and

[1] The authors consider a measurement of the attenuation more fundamental than a study of wavelet amplitude and breadth. We, therefore, have not emphasized wavelet amplitude and breadth. It is interesting to note, however, that for 6 records (same data used to compute results of Figure 9) the wavelet amplitude decreased as the -1.98, -1.99, -2.04, -2.15, -2.16, and -2.26 powers of travel time. These same records indicate that wavelet broadening can be satisfactorily represented by a relation of the form $b=a^{nt}$, where a and n are constants, t is travel time, and b is wavelet breadth. If one attempts to fit the data to the expression $b=t^n$, the exponent is approximately 0.25. These figures compare with -2.50 and 0.50 reported by Ricker.

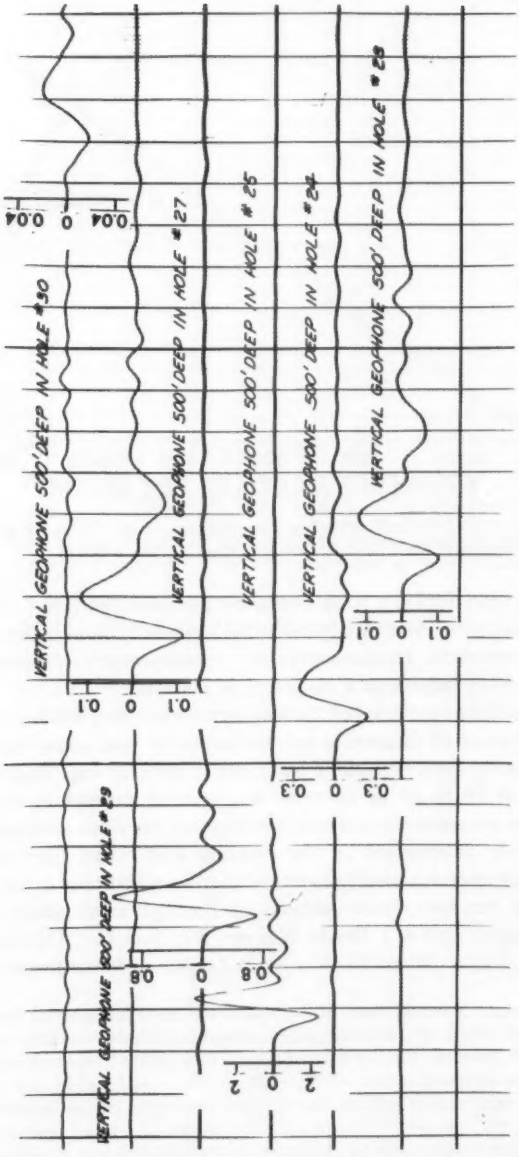

VERTICAL GEOPHONE 500' DEEP IN HOLE #30
0.04 0 0.04
VERTICAL GEOPHONE 500' DEEP IN HOLE #27
0.1 0 0.1
VERTICAL GEOPHONE 500' DEEP IN HOLE #25
0.3 0 0.3
VERTICAL GEOPHONE 500' DEEP IN HOLE #24
0.1 0 0.1
VERTICAL GEOPHONE 500' DEEP IN HOLE #23
0.1 0 0.1
VERTICAL GEOPHONE 500' DEEP IN HOLE #29
0.8 0 0.8
2 0 2

FIG. 10. Horizontally traveling shear waves generated by dropping a weight on the bottom of a 500-ft borehole. Record D. (Amplitudes are expressed in units of cm/sec$\times 10^{-4}$.)

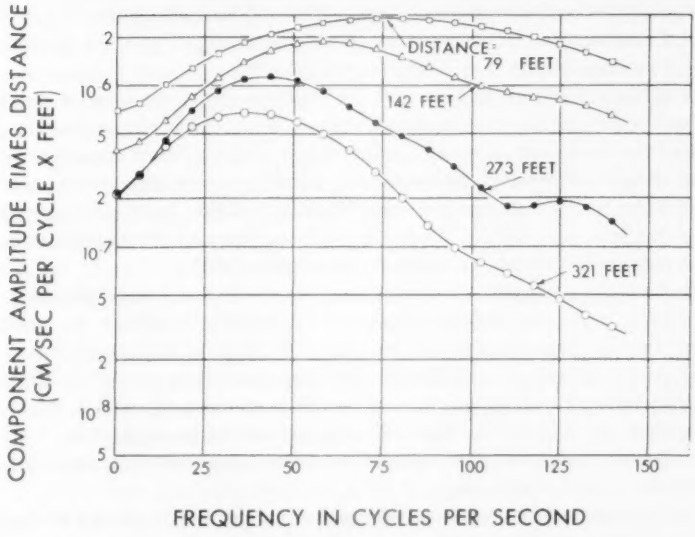


FIG. 11. Spectra of horizontally traveling shear waves generated by dropping a weight on the bottom of a 500-ft borehole. Record D.

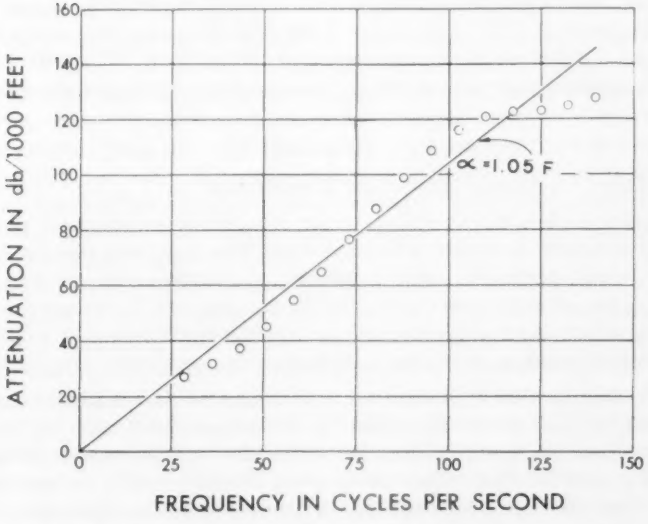


FIG. 12. Attenuation of horizontally traveling shear waves generated by dropping a weight on the bottom of a 500-ft borehole. Record D.

thick carbonate and evaporite sections of West Texas (Magnolia No. 1 Hefflefinger, Roosevelt County, New Mexico) have been logged using Magnolia's two-receiver velocity logger. These wells check velocities obtained from conventional geophone surveys within one percent. (A single receiver type logging instrument was used to obtain the velocity log of Figure 1. Since this is not an absolute measurement the instrument is usually calibrated by a conventional geophone survey.)

An analysis of velocity measurements on cores under appropriate conditions of temperature and pressure is beyond the scope of this paper. It can be stated, however, that no significant dispersion has been reported for frequencies as high as one megacycle (Wyllie, Gregory, and Gardner, 1956).

The absence of dispersion is significant. In the broad field of physics it is indeed rare to find a transmission system which exhibits amplitude discrimination without the corresponding phase distortion. We believe that consolidated earth materials do just this, at least for the low frequency range employed in geophysical prospecting. In the preparation of synthetic seismograms and in the study of reflection wave shapes, the effects of attenuation can be represented by a filter which attenuates high frequencies and produces a constant time delay (no phase distortion) at all frequencies.

The absolute value of attenuation quoted in this paper applies to the Pierre shale to a depth of 1,000 ft. By estimating the reflection coefficient of the base of the Pierre shale on the basis of the velocity logs in the area, one may compute from reflection data the attenuation of the entire 4,000-ft section of Pierre shale. In this manner we have estimated the attenuation of the entire section of 4,000 ft of the Pierre shale as 2.0 ± 1.0 db per 1,000 ft at 50 cycles. This compares with 6.0 db per 1,000 ft for the depth interval of 250 to 750 ft (Figure 9). Both sets of measurements may be valid if we assume that attenuation decreases with depth.

APPENDIX

Requirements for Accurate Attenuation Measurements

A study of the changes of wave shape of a seismic wavelet as it propagates through the earth does require extreme care. This is equally true for measurements of peak amplitude, wavelet breadth, and attenuation. Filtering by the recording instruments, poor coupling of the detector, and inhomogeneities of the earth contribute to wavelet broadening. We believe the following requirements are necessary for an accurate study of attenuation and wavelet propagation.

1. A thick section of uniform material is needed. In the case of the Pierre shale a thickness of approximately 500 ft is required.
2. Attenuation determinations should be made only for signals produced by the *SAME SHOT*. "One cannot shoot a second time in the same hole because the same hole is not there anymore."[2] Even small charges and caps

[2] Quotation attributed to Dr. J. P. Woods.

do not accurately reproduce pulse amplitude and wave form on successive shots. The practice (Ricker, 1953) of increasing the shot-detector distance by moving the shot upward to shallower depths is very misleading. In general, shallow shots produce lower frequency signals, and therefore give the false impression of excessive high frequency attenuation and wavelet broadening.

3. Two or more detectors should be positioned in a straight line path from the shot to minimize the effect of inhomogeneities. A vertical travel path minimizes the effects of anisotropy.
4. The detectors should have uniform response to earth motion over the entire frequency range of the attenuation study. If geophone clamps are employed, one must avoid mechanical resonance. The mass of the clamp and stiffness of the coupling to the borehole wall determine the primary resonant frequency of the system. In general, it is necessary to keep the mass of the clamp small (less than 10 lb) and the pressure on the borehole wall high (greater than 200 psi). No geophone clamp can be considered reliable until its response, clamped in place, has been determined. The use of pressure gauges is questionable. Coupling of an acoustic signal into the borehole fluid depends upon local variations of the rigidity of the borehole wall.
5. A wideband recording system with calibrated and stabilized gain is required. The impulse response or the amplitude and phase response should be measured.

Recording System

To a first approximation the earth and a geophone may be treated as a low-pass resonant system which should exhibit flat response in the frequency region below the resonant peak. In order to insure that the resonant peak occurs at a frequency well above that of the normal recording band, it is necessary to employ a geophone clamp of low mass and rigid clamping to the borehole wall. In general, geophone clamps which depend only upon gravity for the clamping force do not meet this requirement.

The geophone clamps employed in this work (Figure 13) consist of two cylindrical half shells which are expanded by a hydraulic mechanism to provide the necessary clamping action. In one half shell four miniature geophones are imbedded in plastic which is mechanically isolated from the second shell by teflon gaskets. The hydraulic clamping action is obtained by releasing nitrogen gas under 2,000 psi from the cylinder positioned above the clamp. This actuates the piston between the cylindrical half shells which then forces the half shells against the opposite sides of the borehole. The release of the system is obtained by breaking one of the copper tubing pressure lines which is attached to the strain member of electrical cable. Of the four geophones mounted in the clamp, three serve to measure the vertical and horizontal components of motion while the fourth is

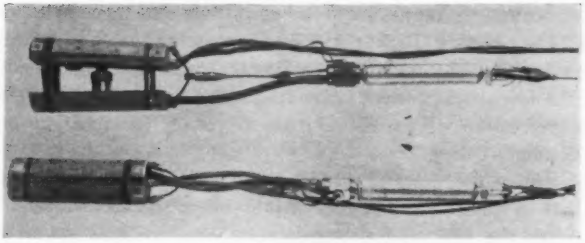


FIG. 13. Geophone clamp.

employed as a driver unit to test the effectiveness of the geophone clamp. This test was made by observing the output of one vertical geophone while a second geophone was being driven at a constant current over the frequency range of interest.

For the Pierre shale, the major resonant peak varies from 1,200 to 2,000 cps, but for any one geophone clamp position the response characteristic was constant. Furthermore, by comparing this response with that of the geophone clamp assembly hanging freely on long rubber bands (Figure 14), one may estimate the response of the system in a manner similar to that employed by Washburn and Wyllie (1941). On this basis, the high frequency response of the clamp was down approximately 10 percent at 450 cps. Since the response at low frequencies is limited only by the response of the geophones themselves, the overall band of the geophone clamp is then accurate to within 10 percent from 20 cycles to 450 cycles.

The pressure gauges used in this work show excellent response to pressure variations over the frequency range from 5 cps to 20 kc. However, it should be recognized that the acoustic coupling from the formation to the borehole fluid depends upon local variations of elastic properties in a borehole wall. The wave forms observed with pressure gauges (Figure 6) do frequently show additional legs of appreciable amplitude which are not observed on the corresponding signals measured with geophone clamps. We, therefore, believe that geophone clamps are more reliable, and we have used them in most of our work.

The 6-channel, high frequency recording truck employed combines broadband linear amplifiers and a high speed, drum-type oscillographic recorder to provide a band width of 5 to 2,000 cps. The amplifiers consist of an input cathode follower, three voltage amplifier plug-in units, and a power output stage. Stable gain and flat frequency response is achieved by employing 20 db negative feedback for each amplifier unit. This unit type construction also permits the use of three independent interstage plug-in filters which are unaffected by the amplifier feedback networks. With the filters not used, the amplifier response is flat within three percent from 3 to 20,000 cps. Gain calibration is achieved by employing precision attenuators in conjunction with a calibration oscillator, the output of which is monitored at a high output level by a diode-type AC voltmeter.

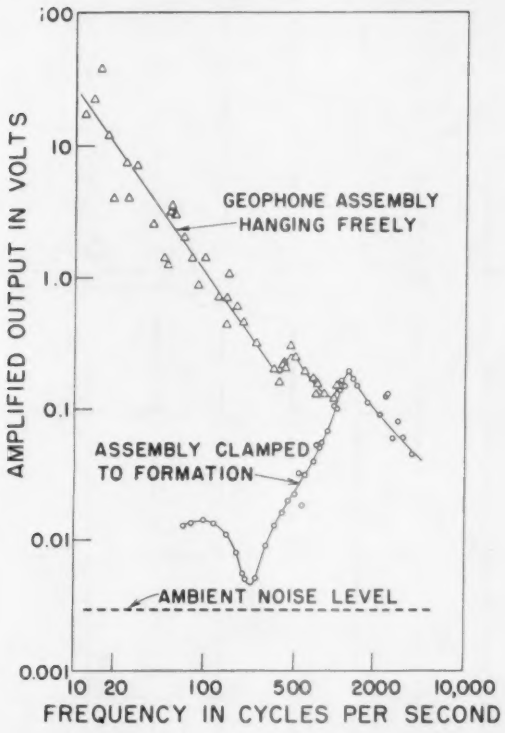


FIG. 14. Geophone clamp response for constant current excitation.

A modified Hathaway S14-C oscillographic recorder with a drum-type film magazine provides recording speeds up to 400 inches per second. Timing lines are reproduced at millisecond intervals. The galvanometers have an undamped natural frequency of 5,500 cps, but fluid damping employed by the manufacturer gives a response which is down 5 percent at 2,000 cps.

The geophone clamps described above limit the frequency response of the complete recording system to the band of 20 to 450 cps. However, with the barium titanate pressure gauges the system is limited by the amplifier-recorder combination to the band of 5 to 2,000 cps.

Fourier analyses were carried out by a digital computer from the digitized records. The field records were enlarged to eight times normal, and amplitudes were measured at 0.25 millisecond intervals.

A test of the uniformity of the 5 channels was conducted by placing 5 geophone clamps at the same depth, 310 ft, in 5 boreholes. The signal from a shot at a depth of 700 ft was recorded and Fourier analyses were made for each channel (Figures 15 and 16). Since all boreholes were grouped within a circle of

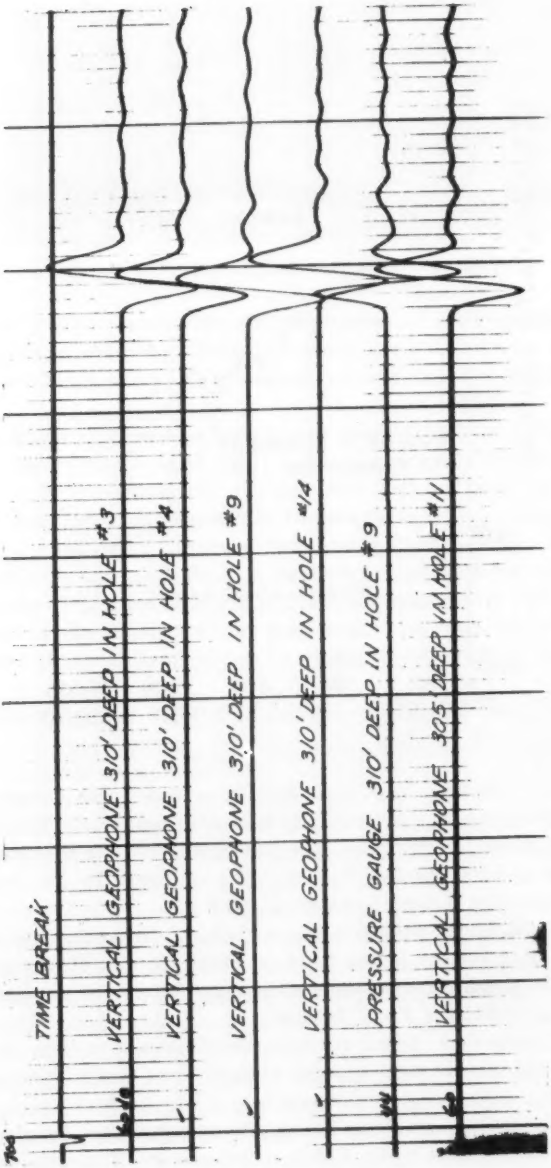

TIME BREAK
VERTICAL GEOPHONE 3/0' DEEP IN HOLE #3
VERTICAL GEOPHONE 3/0' DEEP IN HOLE #4
VERTICAL GEOPHONE 3/0' DEEP IN HOLE #9
VERTICAL GEOPHONE 3/0' DEEP IN HOLE #14
PRESSURE GAUGE 3/0' DEEP IN HOLE #9
VERTICAL GEOPHONE 305' DEEP IN HOLE #11

FIG. 15. Geophone huddle test. Source—Booster charge at a depth of 700 ft.

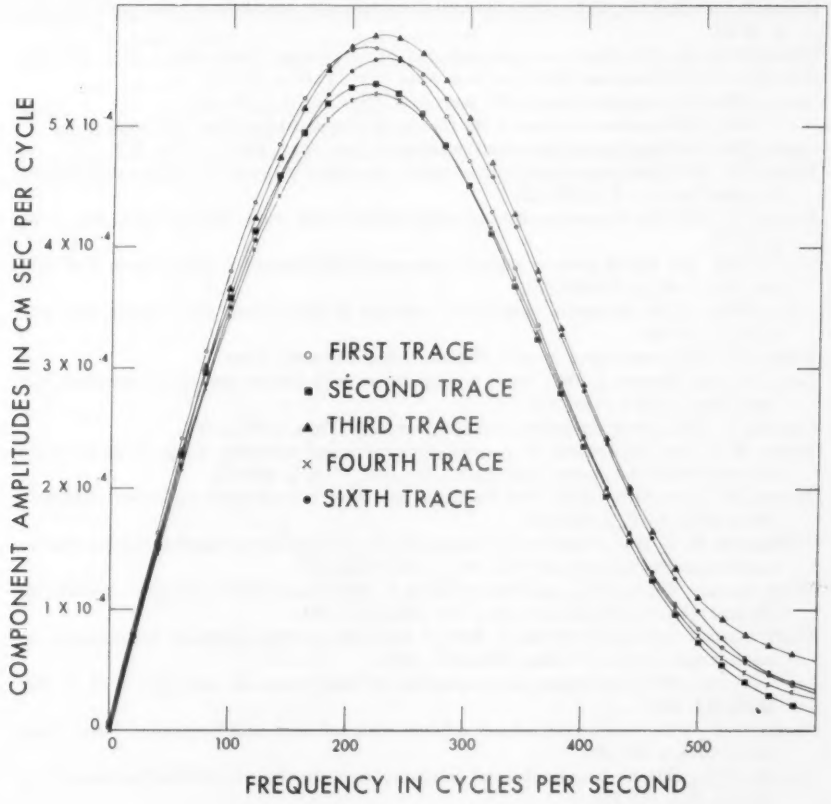


FIG. 16. Spectra of geophone huddle test.

a radius of 15 ft, the travel path was approximately vertical. The degree of similarity of the spectra of Figure 16 is the best measure of the precision of attenuation measurements.

REFERENCES

Birch, Francis, and Bancroft, Dennison, 1938a, Elasticity and internal friction in a long column of granite: Bull. Seis. Soc. Am., v. 28, p. 243–254.

———, ———, 1938b, The effect of pressure on the rigidity of rocks: Jour. Geol., v. 46, p. 59–141.

Birch, Francis, 1942, Handbook of physical constants: Geol. Soc. Amer., Special Papers Number, v. 36, p. 88–92.

Born, W. T., 1941, The attenuation constant of earth materials: Geophysics, v. 6, p. 132–148.

Bruckshaw, J. McG., and Mahanta, P. C., 1954, The variation of the elastic constants of rocks with frequency: Petroleum, v. 17, p. 14–18.

Collins, Francis, and Lee, C. C., 1956, Seismic wave attenuation characteristics: Geophysics, v. 21, p. 16–40.

Duvall, Wilbur I., 1953, Strain-wave shapes in rock near explosions: Geophysics, v. 18, p. 310–323.

Gross, B., 1947, On creep and relaxation: Jour. Appl. Phys., v. 18, p. 213–221.

———, 1948, On creep and relaxation II: Jour. Appl. Phys., v. 19, p. 257–264.

———, 1953, Mathematical structure of the theories of visco-elasticity: Paris, Hermann.

———, 1950, Frictional loss in visco-elastic substances: Jour. Appl. Phys., v. 21, p. 185.

Jeffreys, H., 1931, Damping in bodily seismic waves: Monthly Notices Royal Astronomical Society, Geophys. Suppl., v. 2, p. 318–323.

Knopoff, L., 1956, The attenuation of compression waves in lossy media: Bull. Seis. Soc. Am., v. 46, p. 47–56.

———, 1956, The seismic pulse in materials possessing solid friction, I: plane waves: Bull. Seis. Soc. Am., v. 46, p. 175–183.

———, 1954, On the dissipative visco-elastic constants of higher order: Jour. Acoust. Soc. Am., v. 26, p. 183–186.

Kolsky, H., 1953, Stress waves in solids: Oxford, Oxford University Press.

Lee, E. H., and Kanter, I., 1953, Wave propagation in finite rods of visco-elastic material: Jour. Appl. Phys., v. 24, p. 1115–1122.

Lomnitz, C., 1956, Linear dissipation in solids: Jour. Appl. Phys., v. 28, p. 201.

Mason, W. P., and McSkimmin, H. J., 1947, Attenuation and scattering of high frequency sound waves in metals and glasses: Jour. Acoust. Soc. Am., v. 19, p. 464–473.

Mattice, H. C., and Lieber, Paul, 1954, On attenuation of waves produced in visco-elastic materials: Trans. AGU, v. 35, p. 613–624.

McSkimmin, H. J., 1951, A method for determining the propagation constants of plastics at ultrasonic frequencies: Jour. Acoust. Soc. Am., v. 23, p. 425–434.

Obert, Leonard, Windes, S. L., and Duvall, Wilbur I., 1946, Standardized tests for determining the physical properties of mine rock: U. S. Bur. Mines R.I. 3891.

Obert, Leonard, and Duvall, Wilbur I., 1949, A gage and recording equipment for measuring dynamic strain in rock: U. S. Bur. Mines R.I. 4581.

———, ———, 1950, Generation and propagation of strain waves in rock—part I: U. S. Bur. Mines R.I. 4683.

Parfitt, G. G., 1949, Energy dissipation in solids at sonic and ultra-sonic frequencies: Nature (London), v. 164, p. 489–490.

Quimby, S. L., 1925, On the experimental determination of the viscosity of vibrating solids: Phys. Rev., v. 25, p. 558–573.

Ricker, Norman, 1943, Further developments in the wavelet theory of seismogram structure: Bull. Seis. Soc. Am., v. 33, p. 197–228.

———, 1944, Wavelet functions and their polynomials: Geophysics, v. 9, p. 314–323.

———, 1951, The form and laws of propagation of seismic wavelets: Proc. Third World Petroleum Congress sec. I, p. 514–536. (Same as Richter (1953).)

———, 1953, The form and laws of propagation of seismic wavelets: Geophysics, v. 18, p. 10–40.

———, and Sorge, W. A., 1951, The primary seismic disturbance in shale: Bull. Seis. Soc. Amer., v. 41, p. 191–204.

Schreuer, E., 1952, The thermal damping of elastic vibrations: Z. Physik, v. 131, p. 619–628.

Sezawa, K., 1927, On the decay of waves in visco-elastic solid bodies: Bull. Earthq. Res. Inst., Tokyo Univ., v. 3, p. 43–53.

Thompson, W. T., 1950, Transmission of elastic waves through a stratified sodium medium: Jour. Appl. Phys., v. 21, p. 89–93.

Van Melle, F. A., 1954, Note on "The primary seismic disturbance in shale," by N. Ricker and W. A. Sorge: Bull., Seis. Soc. Am., v. 44, p. 123–125.

Washburn, Harold, and Wiley, Harold, 1941, The effect of the placement of a seismometer on its response characteristics: Geophysics, v. 6, p. 116–131.

Wegel, R. L., and Walther H., 1935, Internal dissipation in solids for small cyclic strains: Physics, v. 6, p. 141–157.

Wyllie, M. R. J., Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, p. 41–70.

Zener, Clarence, 1948, Elasticity and anelasticity of metals: Chicago, University of Chicago Press.

———, 1938, Theory of internal friction in metals, II: Phys. Rev., v. 53, p. 90-99.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 440-458, 9 FIGS.

ELIMINATION OF SECONDARY PRESSURE PULSES IN OFFSHORE EXPLORATION (A MODEL STUDY)*

WILLIAM C. KNUDSEN†

ABSTRACT

The behavior of the gas bubble generated by explosive charges fired below the ocean's surface has been studied by means of a scale model. The motion of the bubble was recorded using a high-speed camera. A small pressure detector was used to record the pressure variation near the bubble. The behavior of the bubble generated by the equivalent of a 15-lb charge was studied with the bubble subjected to the following boundary conditions: a single charge at various depths below the liquid surface, two charges on a vertical axis at various separations and various depths, two charges on a horizontal axis at various separations, a single charge at various separations below a solid plate, and a single charge at various separations to the side of the solid cylinder. Of these methods, the only one which appeared promising was the location of two charges on a vertical axis with both charges within 20 ft of the surface.

INTRODUCTION

When an explosive charge of the weight used in seismic exploration is exploded below the surface of a body of water at a depth greater than about 5 ft, secondary pressure pulses are generated in addition to the initial pressure pulse (Cole, 1948). The first secondary pulse has an amplitude of the order of one-tenth the initial shock wave, and the succeeding pulses are much weaker. The secondary pulses occur after the initial pressure pulse at intervals of a few tenths of seconds.

The occurrence of the secondary pressure pulses presents a difficulty in offshore exploration. The direct arrivals of the pulses interfere with shallow reflections of the initial shock wave. More serious, however, is the fact that a set of reflections from the underlying section will be associated with each secondary pressure pulse. The resulting seismogram is composed of several series of reflections, one delayed behind the other (Lay, 1945). Needless to say, it is difficult to obtain reliable information from such seismograms.

To avoid this difficulty, it is the present practice to explode the charge at a depth less than or equal to about 5 ft. When the charge is exploded at these depths, it is found that the secondary pressure pulses do not occur.

There are reasons why it is desirable to overcome the restriction of the charge to the first 5 ft of ocean depth. It may be possible to get more acoustic energy out of a given charge size, if the charge is fired at a depth greater than 5 ft. In some areas, there is a restriction on charge size so that more energy out of the maximum charge size would increase the depth from which reflections can be recorded.[1] It is also possible that exploding the charge at greater depths will be

* Paper read at the 26th Annual Meeting of the Society at New Orleans on October 31, 1956. Manuscript received by the Editor December 20, 1957.

† California Research Corporation, La Habra, California.

[1] This paper does not attempt to answer the question of acoustic energy increase caused by lower-

helpful for purely geometrical reasons. The acoustic behavior of a mechanical system depends on the source position, and locating the source at certain positions will emphasize or diminish the amplitude of certain modes of vibration.

The object of the research reported here was to investigate means of eliminating the secondary pressure pulses when the charge is fired at depths greater than 5 ft. In what follows, a simplified physical description of the bubble behavior will be given together with the modeling results of several schemes for eliminating the secondary pressure pulses.

DESCRIPTION OF PHENOMENON

It has been determined by experiment (Cole, 1948) that the initial shock wave generated by TNT and similar explosives carries away approximately one-half of the original chemical energy of the charge.

After the passage of the shock wave away from the charge position, the remaining one-half of the original energy is contained in the form of the potential energy of hot gases at high pressure in a small spherical bubble and in the kinetic energy of the outwardly flowing water. Under the influence of this pressure the bubble surface expands. As it expands the pressure of the gas diminishes in obedience to the adiabatic gas expansion relation, $PV^{\gamma}=k$. P is the pressure; V, the volume of the bubble; γ, the ratio of the specific heats, a constant depending on the kind of gas; and k, a constant depending on the quantity of gas. The pressure of the gas drops to the hydrostatic pressure at the charge depth when the radius of the bubble is approximately 0.65 of the maximum radius, a_m. As the radius continues to expand beyond 0.65 a_m, the pressure in the bubble drops below hydrostatic pressure, and the motion is decelerated until the radial velocity of the bubble surface is zero. The radius of the bubble at this time is the maximum value, a_m, and the pressure of the gas is roughly one-fifth the hydrostatic pressure. The energy of oscillation is in the potential form, and it is represented by the cavity in the ocean. With the pressure in the bubble less than hydrostatic, the water is accelerated toward the center of the bubble. As the volume decreases, the pressure rises to the hydrostatic value and above as the water overshoots the equilibrium radius. The pressure rises until the inward flow of water is stopped. At this minimum radius, the energy of oscillation is again in a potential form, the form being mostly internal energy of the gas. At this minimum radius, the pressure is large enough to generate an acoustic pulse, that is, one which travels outward at the velocity of sound in the ocean. This is the secondary pressure pulse. The above sequence of events is then repeated but with less energy of oscillation. The energy of oscillation in the second period is less because some energy is removed in the form of the secondary pressure pulse and some, a greater amount, presumably in turbulence, when the radius is near its minimum value.

---

ing the charge below 5 ft. The model used is not appropriate for quantitatively modeling the generation of shock waves.

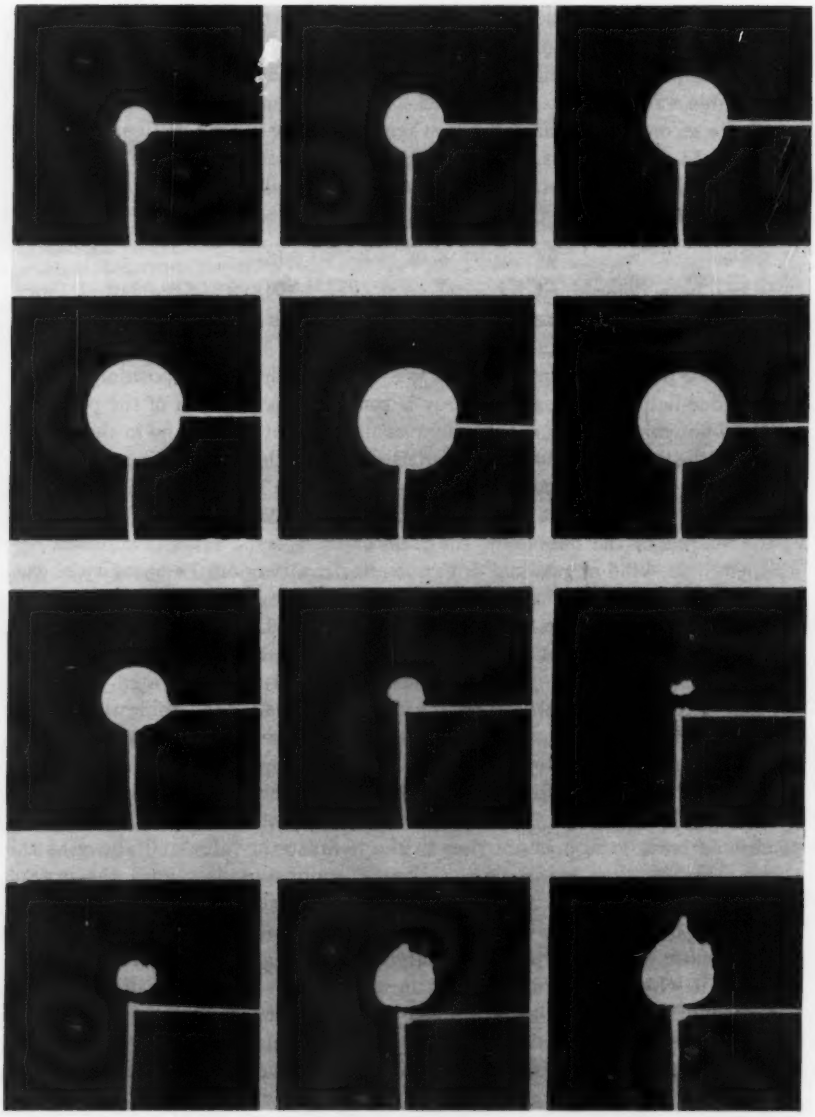


FIG. 1. Model equivalent of a 15-lb charge 100 ft below ocean surface. Time increases from left to right.

Figure 1 shows a sequence of Schlieren photographs of a model explosion. The charge is equivalent to 15 lb of explosive at 100-ft depth. Time increases from left to right and then down to the next row. The first expansion and collapse and portion of the second expansion is shown. The cross-section effect is produced by the Schlieren photography. The two rods, one from the right and one from the bottom, are the two electrodes of a spark gap which was used to generate the bubble. Figure 2 shows the measured radius as a function of time for the model bubble. The units are appropriate for the prototype.

The problem of eliminating the secondary pressure pulse ultimately reduces to one of transforming an appreciable fraction of the bubble oscillation energy into some other form during the first period. It was pointed out above that the

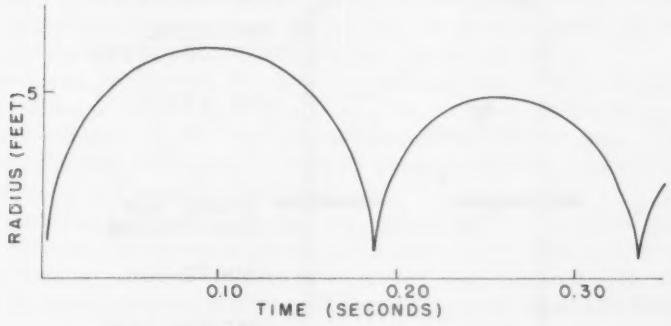


FIG. 2. Bubble radius vs time. Units are appropriate for the prototype.

secondary pulses are generated by the high pressures occurring at the time of bubble collapse. To prevent the high pressure buildup, it is necessary to prevent the transfer of the bubble oscillation energy back into the internal energy of the gas after the initial expansion.

It is instructive to compute the power transformation that must be accomplished to eliminate the bubble oscillation. The energy of oscillation resulting from the detonation of a 15-lb charge is about 1.5×10^7 joules. For half of this energy to be transformed in 0.18 sec, it is necessary to transform at an average rate of about 4×10^7 w or about 0.5×10^5 hp during the interval. These figures give an indication of the magnitude of the problem involved in transforming the bubble oscillation energy.

METHOD OF EVALUATION

To evaluate several possible methods of eliminating the secondary pressure pulses, model experiments have been performed. The model consisted of a volume of oil contained in a vacuum tank. The oil represented the ocean. (The need for a vacuum is based on model theory as discussed in the appendix.) Figure 3 is a

schematic drawing of the vacuum tank, oil, and associated apparatus. The bubbles were generated by discharging a condenser across a spark gap. The tank was provided with three vacuum sealed openings to permit adjustment and movement of three spark gaps. Two of them, with horizontal movement, are illustrated in the figure. The third extended down from the lid of the tank and had vertical movement. The spark gaps could be fired either singly or in pairs. A small barium titanate pressure probe was located in the oil to detect the pressure pulses. Viewing ports (not shown in the figure) were located in the walls of the

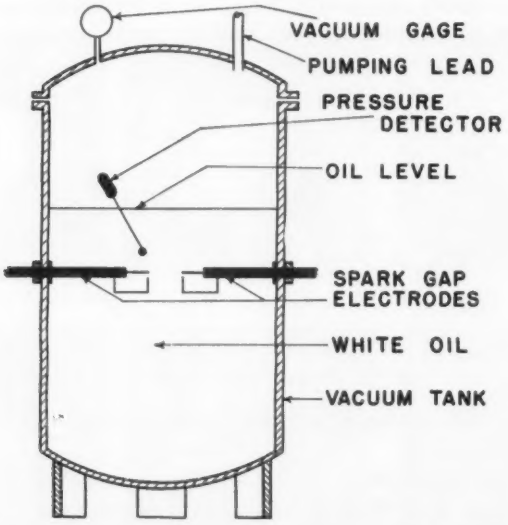


FIG. 3. Experimental model showing arrangement of parts. Viewing ports used in photographing the motion are not shown.

tank so that the motion of the bubbles could be recorded with a high-speed camera. Various other pieces of apparatus, such as a plate or a rod, were located in the tank to model their use in the field.

The power supply for the spark gaps consisted of a high voltage rectifier for charging two $\frac{2}{3}$-microfarad condensers to 8,000 volts. Each condenser supplied one spark gap. The discharge of each condenser was controlled by a hydrogen thyratron, which was fired, in turn, by a trigger initiated by the operator or by the high-speed camera.

The motion of the bubble was recorded by a Kodak high-speed camera. The frame rate was approximately 2,600 frames per sec. At this rate, there were about 36 frames per cycle of oscillation. To illustrate clearly the outline of the bubble

surface, a Schlieren lighting arrangement was used. The Schlieren photographs are essentially vertical cross-sections of the bubble.

Two criteria were used to evaluate whether a given configuration would be useful in eliminating the secondary pressure pulses. The first criterion was the observed motion of the bubble. The motion of the gas bubble radius depends on the pressure in the gas (in addition to other things); hence, a study of the bubble motion as recorded by the high-speed camera gave qualitative information regarding the pressure buildup in the gas. In those examples where a well-defined minimum volume was observed, together with a rapid contraction and expansion before and after, the possibility of a strong secondary pulse was good. Where no such condition was observed, it was inferred that the secondary pressure pulse would be smaller in amplitude. The second criterion was the behavior of the secondary pressure pulse as recorded by the pressure probe located near the gas bubble. In the field, this would be the ultimate criterion.

The correlation between the observed pressure pulse in the model and that for the prototype is not expected to be so good as the correlation between the prototype and the model for the motion of the bubble. Modeling theory indicates that the pulse observed on the model would be narrower in time than the equivalent prototype and would contain less energy.

To overcome as much as possible the modeling difficulty associated with the second criterion, the secondary pressure pulse observed with the bubble exposed to the boundary conditions under investigation was compared with that recorded with the conditions removed. This technique is discussed and illustrated below.

The output of the pressure detector was amplified and applied with or without filtering to the vertical plates of an oscilloscope. Figure 4 illustrates the records obtained. The timing trace (one kc per sec square wave) served to time the events and to calibrate the amplifier. Trace one shows the pressure variation at the detector position when the charge was fired at an equivalent depth of 100 ft with no obstructions near the charge. The trace begins at the time the spark gap breaks down. The first event is a shock wave generated by the breakdown of the gap dielectric (the peak cannot be seen in the figure). Several reflections of this event off the oil-vacuum and oil-tank interfaces then occur with diminishing amplitude and give the trace its broad and fuzzy appearance. About 15 milliseconds behind the beginning of the trace is the first secondary pressure pulse (A) which is in turn followed by its reflections. Another 15 milliseconds behind this event is the second secondary pressure pulse (B). It is smaller in amplitude as a result of energy lost during the first bubble contraction and expansion. (The first secondary pressure pulse on traces 1, 8, and 9 have been retouched to make them visible on the print.)

Traces 2 and 3 were taken with the physical conditions unchanged from those occurring in trace 1. The signal is filtered, however, with a band width equivalent to the normal seismic band. The filtering for traces 4 and 5 is the same as that for

2 and 3, but a solid cylinder was placed close to the spark gap in the model. Traces 6 and 7 were taken with the cylinder in contact with the spark gap, with no filtering, and with the scope sweep delayed and expanded to give a more detailed picture of the first secondary pressure pulse. Traces 8 and 9 are the same as 6 and 7 with the exceptions that the solid cylinder was removed, and the amplifier gain was smaller. The bottom trace is an approximately one kc per sec square wave and is used to calibrate the timing for traces 6 through 9.

With the exception of the first trace, two traces were recorded with each filter setting and physical condition to improve confidence in the results. It was found that the spark gaps did not break down identically each time, and, as a result, the energy in the bubble was not identical. Traces 8 and 9 illustrate a slightly different period for the collapse resulting from a small difference in bubble oscillation energy.

Measurements on the record revealed that the presence of the solid cylinder reduced the unfiltered peak amplitude by a factor of about 9, although, on the filtered traces, it reduced the amplitude by a factor of only 1.3. Evidently, the presence of the cylinder reduced the symmetry of the flow sufficiently to reduce the peak amplitude of the very sharp pulse illustrated in traces 8 and 9, but the broader, lower amplitude behavior was little affected. The filtered traces, which were relatively insensitive to the high frequencies associated with the sharp peak, were reduced only slightly.

The same type of record as illustrated in Figure 4 was made for each method of eliminating the secondary pressure pulse. The results will be given when the particular method is described.

It is necessary in model studies to consider how reliably the model behavior represents the prototype behavior. For the model used in this study, theoretical considerations indicate that the model flow-behavior should be a reliable indication of the prototype behavior. In addition, the observed behavior of the model did duplicate field behavior where a comparison was possible. For example, when a 15-lb charge at 10-ft depth below the ocean surface was modeled, secondary pressure pulses were recorded consistently. When the same charge was placed at a depth equivalent to 5 ft, there was no secondary pressure pulse for 7 of the 10 shots. In field work, the depth at which the secondary pressure pulses are eliminated is about 5 ft. The most serious failure of the model from a theoretical point of view occurs in the amount of energy radiated as an acoustic wave during the collapse of the bubble. The amount radiated in the model is expected to be less than it would be if all the pertinent parameters were properly modeled. The peak amplitude, however, is expected to be correctly modeled.

DESCRIPTION AND RESULTS OF SEVERAL ELIMINATION METHODS

The present method of eliminating the secondary pressure pulse is to locate the charge close enough to the surface so that the bubble "blows out." Figure 5

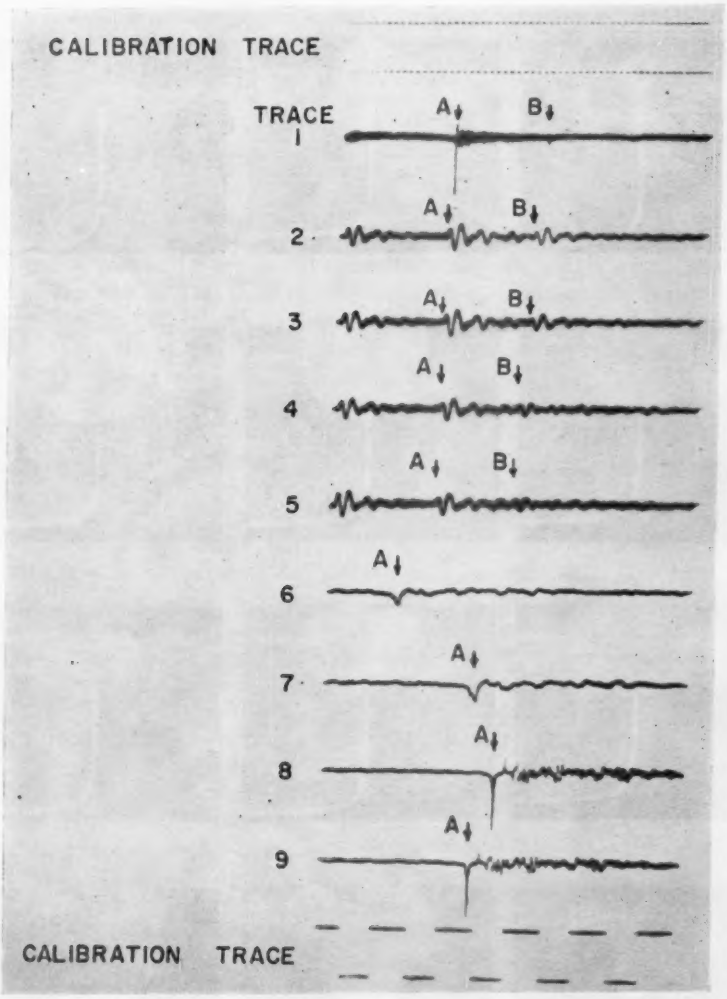


FIG. 4. A typical pressure record. The first calibration trace is a one kc per sec square wave. Trace 1 is an unfiltered pressure recording with no obstacle to bubble motion. A is the first bubble pulse, and B is the second. Traces 2 and 3 are filtered repetitions of trace 1. Traces 4 and 5 are filtered pressure records observed with the bubble motion obstructed. Traces 6 and 7 are unfiltered, expanded, and delayed repetitions of traces 4 and 5. Traces 8 and 9 are repetitions of trace 1 but with expanded time base and delayed. They were recorded with lower gain than traces 6 and 7. The lower calibration trace is a one kc per sec square wave with the same time base as traces 6, 7, 8, and 9.

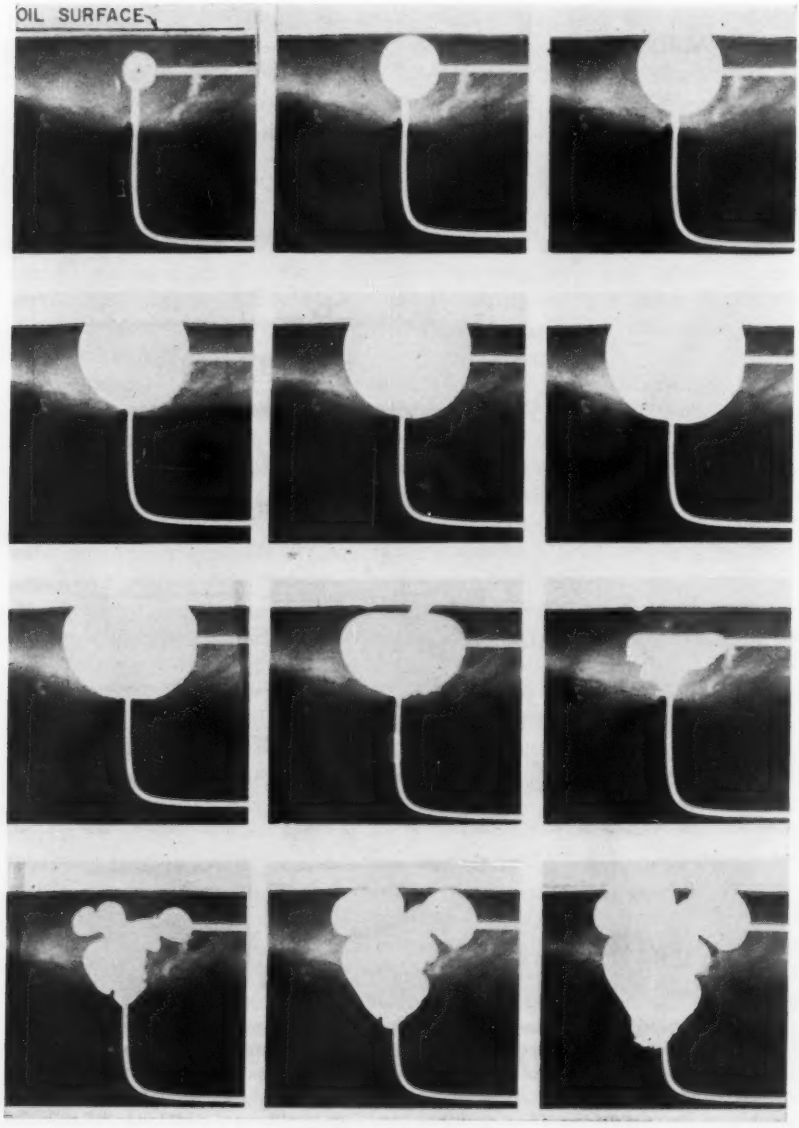


FIG. 5. Model equivalent of a 15-lb charge 5 ft below surface.
Time increases from left to right.

shows a sequence of the photographs of the model behavior for a 15-lb charge at 5 ft.[2] The surface of the liquid is blocked off the photographs, but its position is indicated. The bubble is seen to break the surface, and, as the radius contracts, a vent is observable for a fraction of the motion. The cross-section of the bubble becomes no smaller than that shown. The pressure records showed no secondary pressure pulse above the noise level on the unfiltered trace. The amplitude of any disturbance resulting from the motion was less than 1/22 the secondary pressure pulse produced by the same charge at a model depth of 10 ft. The latter bubble did not break the surface and collapsed to a considerably smaller cross-section. It performed two well-defined oscillations.

These results indicate that, at least under these conditions, the model is behaving very similarly to the prototype. Field experience has demonstrated that 5 ft is about the maximum depth at which a 15-lb charge can be exploded without generating a secondary pressure pulse.

The precise mechanism by which the secondary pressure pulse is eliminated when the charge is placed at 5 ft below the surface is not positively known. However, it is probably the following. By the time the bubble has expanded so that its radius is equal to the depth of the charge, the pressure in the gas is about the same as the hydrostatic pressure at the charge depth. At this point, most of the bubble oscillation energy is associated with the outwardly flowing water. If the surface were not present, the bubble would continue to expand, and the pressure inside the bubble would drop to about $\frac{1}{3}$ of the hydrostatic pressure at the maximum bubble radius. However, with the surface present, the pressure in the bubble cannot be reduced below atmospheric, which is only slightly smaller than the hydrostatic pressure. That is, the atmosphere rushes into the bubble preventing the pressure from being reduced below atmospheric pressure. The pressure difference at maximum radius between hydrostatic pressure and that in the gas bubble is much less than it would be in the absence of the surface; and hence the potential energy available for transfer back into the gas has been considerably reduced.

Another method, which is the subject of a U. S. patent (R. S. Finn; U. S. No. 2,599,245), consists of placing one charge between the surface of the ocean and a second, lower charge. To check this method, two 15-lb charges were modeled at various depths. With one charge at 20 ft and the second at 15 ft below the surface, little decrease (12 percent) in amplitude of the secondary pressure pulse on the filtered pressure record was observed over that of a single charge at 20-ft depth. With the lower charge at 20 ft and the upper charge at 10 ft, the amplitude of the secondary pressure pulse was not observable on the filtered pressure records. The amplitude of the pulse was less than $\frac{1}{3}$ of that from a single charge at 20 ft. Noise on the trace set the detection limit.

With one charge at 15 ft and the second at 10 ft, and also with one charge at

[2] All dimensions given in this section are scaled up to those appropriate for the prototype and are not actual model dimensions. The photographs were not selected at equal time increments.

15 ft and the second at 5 ft, there was no observed secondary pressure pulse above the noise level on the filtered pressure record. In each case, this means that the secondary pressure pulse on the filtered traces was at least a factor of 5 or 6 below that of a single charge at 15 ft. Figure 6 illustrates the bubble behavior for one charge at a depth of 15 ft, the second at 5 ft. Of the two configurations—the shallow charge at 5 ft or at 10 ft below surface—the one with the charge at 5 ft appeared more positive from a consideration of the bubble motion. With the lower charge at 10 ft and the upper charge at 5 ft, there was again no observable bubble pulse on the filtered pressure record. The amplitude of the pulse was less than 1/10 that of a single charge at 10 ft. These results are presented in Table 1.

TABLE 1

Depth 1st Charge (Ft)	Depth 2nd Charge (Ft)	Amplitude Ratio, Filtered*	Amplitude Ratio, Unfiltered†
20	15	0.88	0.12
20	10	<0.12	<0.04
15	10	<0.20‡	<0.02
15	5	<0.07	<0.03

* Ratio of filtered secondary pressure pulse amplitude when both charges are simultaneously exploded to that when only the lower charge is exploded.

† The same ratio but with pressure record unfiltered.

‡ One out of three filtered traces showed no secondary pulse reduction for this configuration.

The sign < indicates that no secondary pulse was observed above the noise on the trace. The stated ratio is for the minimum detectable signal.

The mechanism by which the above method eliminated the secondary pressure pulses is somewhat similar to that of a single charge at 5 ft. Communication is made with the atmosphere, so that the pressure in the gas cannot be reduced to the small value it would have in the absence of the surface. The outwardly flowing motion is, thus, not decelerated as rapidly as normally. This is especially true near the surface, where hydrostatic pressure is very little more than atmospheric. Near the bottom of the two charges, the hydrostatic pressure is about twice atmospheric, so the downward motion is stopped and then accelerated back toward the surface.

An attempt to duplicate the effect of a hard bottom on the bubble motion was made by placing a $\frac{1}{4}$-inch thick brass plate in the model. The film recordings of this motion showed that the bubble did not break the free surface when the plate was at an equivalent depth of 15 ft or greater. At a depth of 10 ft, the bubble did break the surface. The pressure records taken with the plate in place were unreliable because of multiple reflections between plate and free surface.

The methods discussed above are restricted to depths within approximately 20 ft of the surface or to shallow water. The remaining methods to be discussed can be used at greater depths.

A method suggested by R. W. Mann (U. S. Patent 2,604,954), to explode the

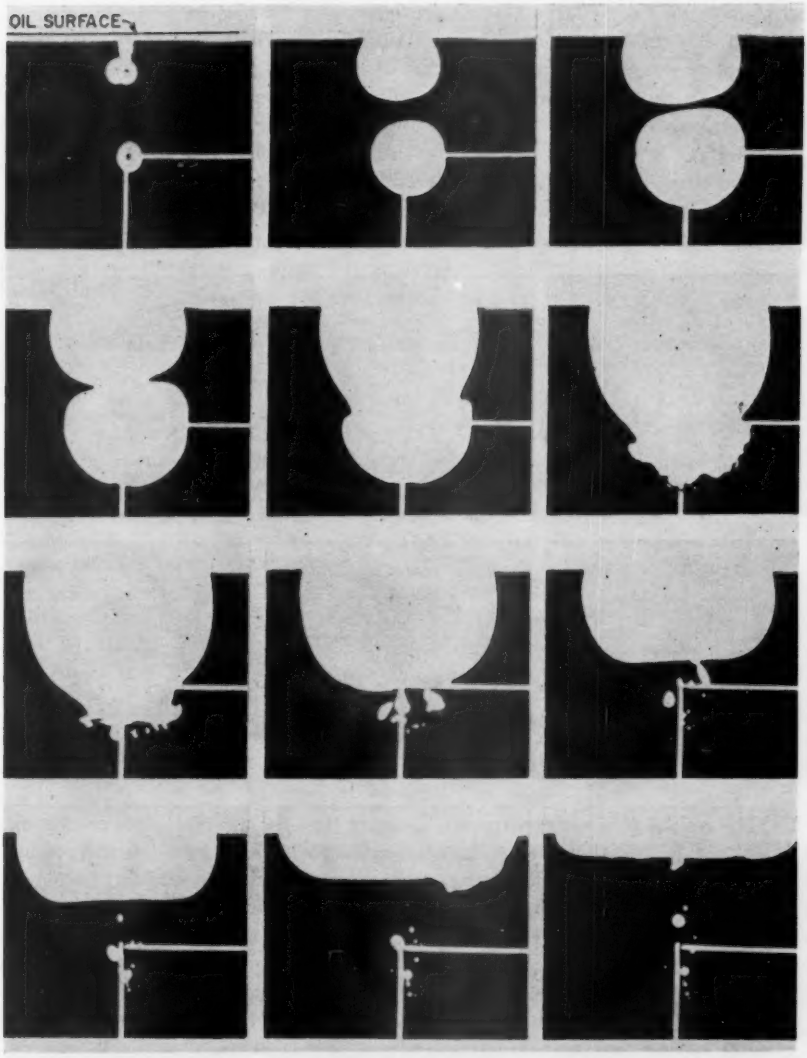


FIG. 6. Model equivalent of one 15-lb charge at 5 ft and a second 15-lb charge at 15 ft below surface. Time increases from left to right.

charge near an obstacle such as a plate or a solid cylinder, has been investigated by modeling a 15-lb charge placed at 1.5, 3.5, and 7.0 ft from a plate or a solid cylinder. The plate was equivalent to a plate 0.8-inch thick and 10-ft square. The density was equivalent to steel, but the modeled plate would behave more rigidly than the prototype. The solid cylinder was equivalent to a steel cylinder 13 ft long and 3 ft in diameter. The pressure record results are presented in Tables 2 and 3. Figures 7 and 8 show the Schlieren photographs of the motion during the first and a portion of the second oscillation for the charge 1.5 ft below the plate and 1.5 ft to the side of the solid cylinder. The depth of the charge is equivalent to 100 ft.

TABLE 2

PLATE

Charge Separation (Ft)	Amplitude Ratio, Filtered*	Amplitude Ratio, Unfiltered†
1.5	0.7	0.14
3.5	1.0	0.20
7.0	1.0	0.30

* Ratio of filtered secondary pressure pulse amplitude when plate or cylinder is in place to that when it is removed.

† The same ratio with the pressure record unfiltered.

TABLE 3

CYLINDER

Charge Separation (Ft)	Amplitude Ratio, Filtered*	Amplitude Ratio, Unfiltered†
1.5	0.8	0.1
3.5	0.9	0.25
7.0	0.9	1.0

* Ratio of filtered secondary pressure pulse amplitude when plate or cylinder is in place to that when it is removed.

† The same ratio with the pressure record unfiltered.

The results of these experiments indicate that the use of a plate or cylinder would not be effective. These obstacles did reduce the observed peak pressure, but the amplitudes of the lower frequency components were not affected strongly. The photographs show a rather well-defined collapse of the bubble in each use.

Another method suggested is that of detonating two charges close to each other (C. H. Carlisle; U. S. Patent No. 2,619,186). This method has been evaluated by modeling two 15-lb charges exploded at horizontal and vertical separations of 7, 14, and 21 ft. The depth is 100 ft. These separations correspond roughly to one, two, and three maximum bubble radii.

The results of the pressure records are given in Tables 4 and 5. Figure 9 shows Schlieren photographs taken of the motion for two horizontal charges placed 7 ft apart.

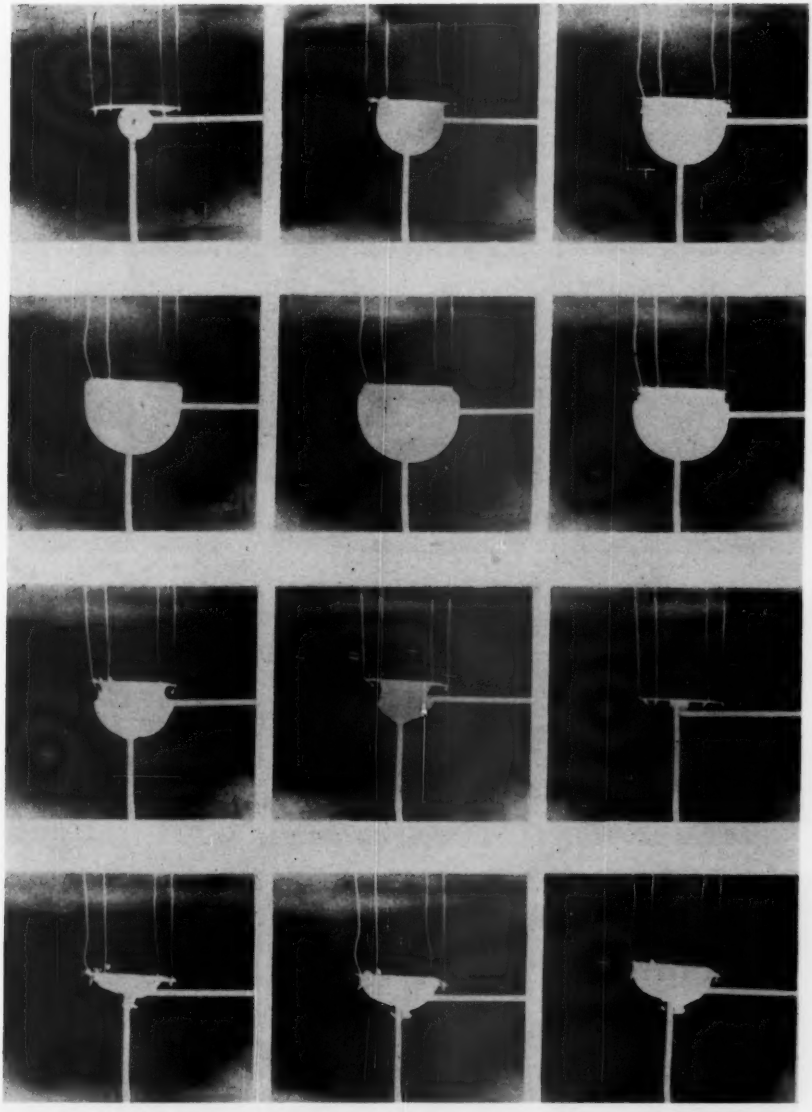


FIG. 7. Model equivalent of a 15-lb charge 100 ft deep and 1.5 ft below a 0.8-inch by 10-ft square rigid plate. Time increases from left to right.

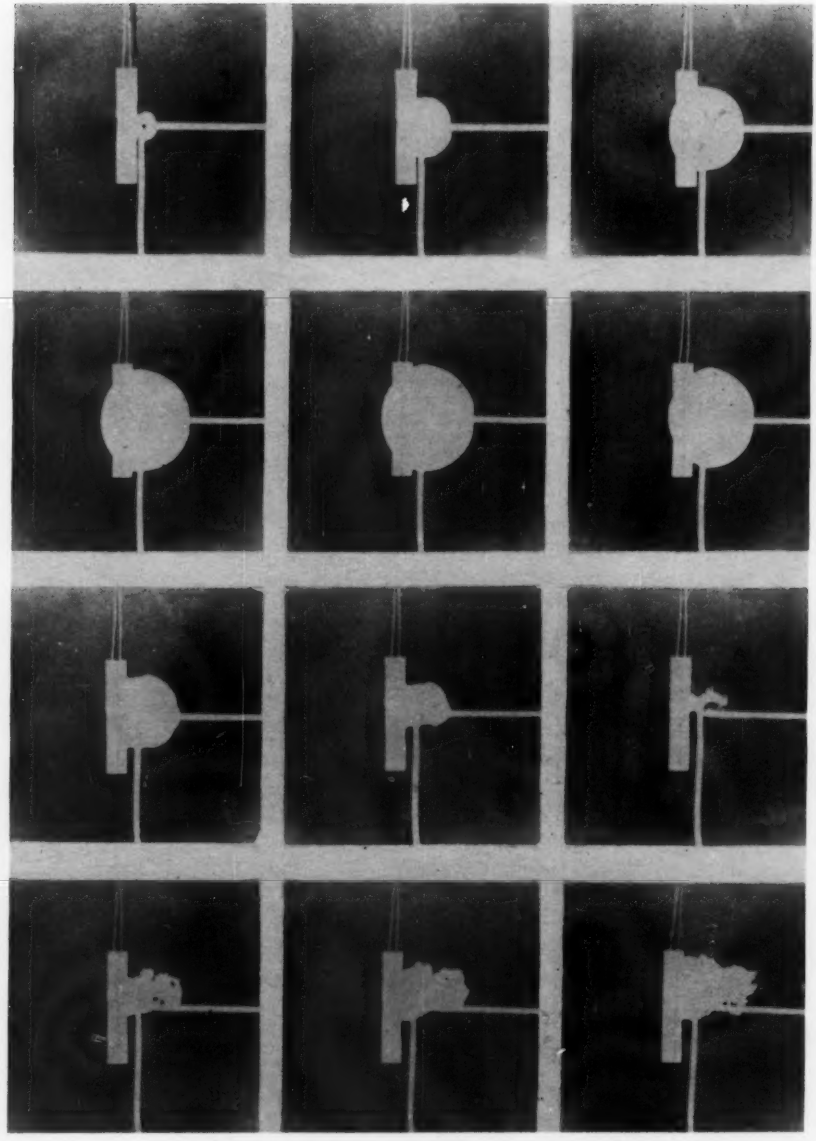


FIG. 8. Model equivalent of a 15-lb charge 100 ft deep at 1.5 ft to the side of a solid steel cylinder 3 ft in diameter and 13 ft long.

TABLE 4

HORIZONTAL SEPARATION

Separation of Charges (Ft)	Amplitude Ratio, Filtered*	Amplitude Ratio, Unfiltered†
7	1.4	0.2
14	0.7	1.0
21	1.8	1.3

* Ratio of filtered secondary pressure pulse amplitude when both charges are exploded to that when only one is exploded.
† The same ratio but with the pressure record unfiltered.

The results obtained on the model for the above configurations indicate that using two charges will not be effective in eliminating the secondary pressure pulse. The peak pressure was reduced below the value for a single charge only for the closest separation. The amplitudes of the lower frequency components were not appreciably affected. The photographs for the 7-ft separation show the two bubbles coalescing into one before the first collapse. At closer separations, the two bubbles would behave even more like a single bubble. At a separation of 14 ft, or approximately a bubble diameter, the bubbles collapsed individually.

Why it is difficult to eliminate the secondary pressure pulses by using simple boundary conditions may be understood with the help of hydrodynamic laws. Calculation of a Reynolds number for the bubble motion shows that inertial forces are large compared with frictional forces throughout most of the fluid volume. It is only close to the solid surfaces that the flow appears viscous. This

TABLE 5

VERTICAL SEPARATION

Separation of Charges (Ft)	Amplitude Ratio, Filtered*	Amplitude Ratio, Unfiltered†
7	1.0	0.2
14	1.4	1.0
21	0.8	1.0

* Ratio of filtered secondary pressure pulse amplitude when both charges are exploded to that when only one is exploded.
† The same ratio but with the pressure record unfiltered.

is true even of the model, in which the viscosity is larger than the properly modeled value. Consequently, only a small part of the bubble oscillation energy is dissipated by viscous flow during the first oscillation. The majority of the energy is represented by potential flow of the fluid, that is, by a non-dissipative type flow.

CONCLUSIONS

The results of this study indicate that of the various methods of eliminating the secondary pressure pulse investigated, only those in which the charges are located within 20 ft of the surface appear promising.

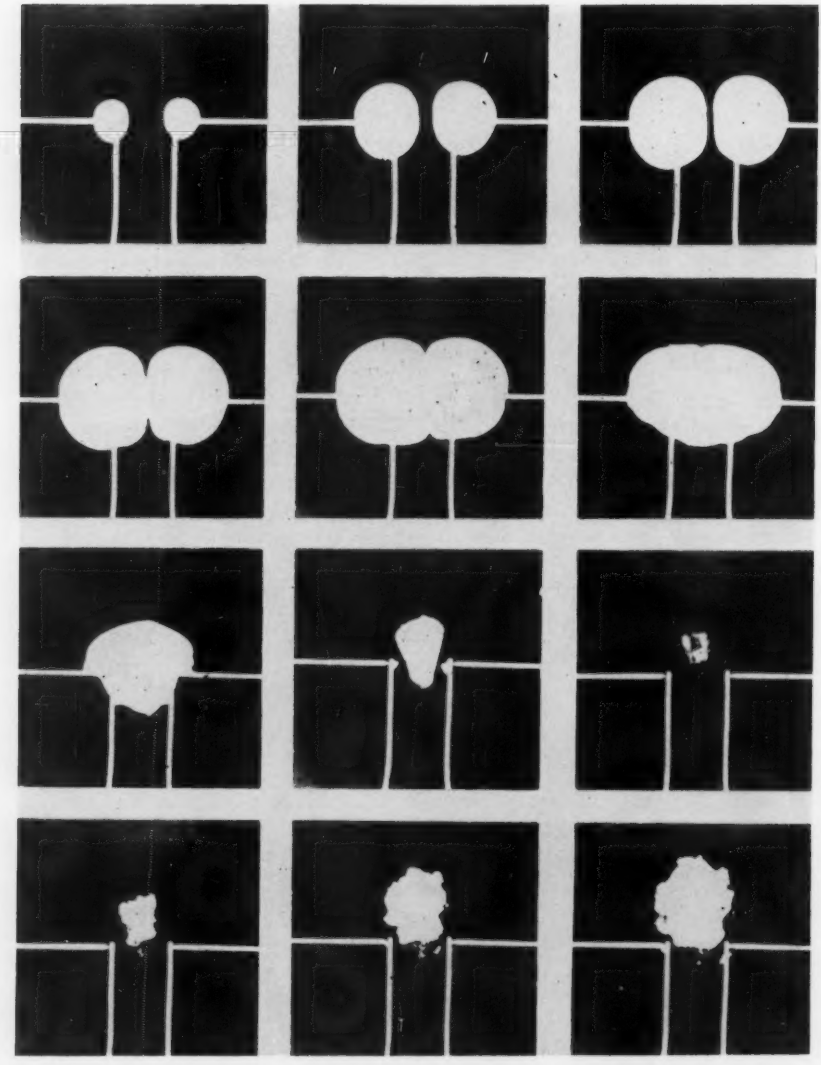


FIG. 9. Model equivalent of two 15-lb charges 100 ft deep and separated 7 ft.

APPENDIX

If a model is to reproduce reliably the behavior of its prototype, it is necessary that all independent, non-dimensional parameters consisting of "significant," independent variables must have the same value in the model as they have in the prototype.

The following is a list of the significant, independent variables associated with the "incompressible" flow of the bubble oscillation.

P_0 absolute hydrostatic pressure at charge location,
ρ_1 density of the liquid,
ρ_i density of any object, such as a solid plate,
D depth of charge below free surface,
L_i any other characteristic length,
g gravity,
μ viscosity,
a_m maximum radius of the bubble,
γ ratio of specific heat of gas at constant pressure to that at constant volume.

The energy of oscillation is measured by a_m. That is, the energy of oscillation is

$$\frac{4\pi P_0}{3} a_m{}^3.$$

Non-dimensional parameters that can be made from the above variables include

$$P_0/\rho_1 g D$$

$$\rho_1/\rho_2$$

$$D/L_i$$

$$P_0{}^{1/2}\rho_1{}^{1/2}D/\mu$$

$$D/a_m$$

$$\gamma.$$

These should have the same values in model and in prototype. Of necessity, g has the same value in both. ρ_1, the density of the liquid, has nearly the same value in model and prototype. It was necessary, therefore, to reduce the air pressure over the oil in the model in order to keep $P_0/\rho_1 g D$ constant. It was possible to keep all the other parameters at the same value in the model as in the prototype with the exception of the one containing the viscosity. Since both P_0 and D were reduced in the model, μ should have been much less for the model liquid than the value for water. Actually, for the white oil used in the model, μ was larger. Even though the viscosity is larger in the model than in the prototype, its effect on the motion is small for most of the methods investigated. It was pointed out

earlier that, when only a small portion of the liquid had to flow close to a surface, the flow was predominantly potential and that viscosity played a small role in the bubble motion.

Another parameter which is unimportant during most of the bubble oscillation, but which is important near the minimum radius, is $c/\sqrt{gD}$. c $(=1/\sqrt{K\rho_l})$ is the velocity of sound in the liquid, where K is the compressibility of the liquid. Near the minimum radius, the pressure gets large enough to compress the liquid, and the compressibility of the liquid is thus significant. To keep this parameter constant, the velocity of sound in the model should have been less than it was. That is, the liquid should have been more compressible. The failure of the model liquid to have the proper smaller compressibility resulted in the secondary pressure pulses being sharper than those generated by large-scale explosions.

REFERENCES

Cole, R. H., 1948, Underwater explosions: Princeton, Princeton University Press.

Lay, R. L., 1945, Repeated P-waves in seismic exploration of water-covered areas: Geophysics, v. 10, p. 467–471.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 459–493, 23 FIGS.

AN EXPERIMENTAL INVESTIGATION OF FACTORS AFFECTING ELASTIC WAVE VELOCITIES IN POROUS MEDIA*

M. R. J. WYLLIE,† A. R. GREGORY,† AND G. H. F. GARDNER†

ABSTRACT

An experimental investigation has been made of the factors which affect the velocity of vibratory signals in porous media. It is shown from the results of experiments carried out on appropriate natural and synthetic porous systems that the time-average formula previously suggested by Wyllie, Gregory, and L. W. Gardner is of considerable utility. This formula states that

$$\frac{1}{V_M} = \frac{\phi}{V_F} + \frac{1-\phi}{V_R}$$

where V_M = velocity measured, V_F = velocity in saturating liquid, V_R = velocity in rock solid, and ϕ = volumetric porosity fraction. The effects are examined of differential compacting pressures on the applicability of this formula to consolidated and unconsolidated rocks. It is shown that the time-average relationship cannot be applied to determine the total volumetric porosity of carbonate rocks which are vugular and fractured. In such rocks, paradoxically, this circumstance may be advantageous because of the lithological information that may be obtained from an appropriate combination of velocity and nuclear log data.

The effects of oil and gas saturation on velocity have been examined experimentally and are found to be comparatively minor. The combination of velocity data with information from electric logs in order to locate zones of oil and gas saturation is shown to be generally valuable; this is particularly so when holes are drilled with oil-base mud.

Some discussion is given of the possible effects on velocity measurements of the relative wettability of rock surfaces by various liquids.

Owing to instrumental limitations, it cannot necessarily be assumed that measurements made in the laboratory are directly applicable to the interpretation of velocity data obtained under field conditions.

INTRODUCTION

The work reported upon in this paper is a continuation of that published by Wyllie, Gregory, and L. W. Gardner (1956). In the previous paper the effect and importance of subjecting specimens to confining pressures during velocity measurements were briefly discussed; nevertheless, most of the experimental data that were presented pertained only to specimens measured at atmospheric pressure.

Data which serve to emphasize the influence of pressure on velocity measurements made on porous media have recently been published by Hicks and Berry (1956). For the purposes of the present paper virtually all measurements have been made on specimens subjected to pressures and pressure differentials which, we believe, are comparable to those sustained by rocks in their natural environment and in the depth range now of practical importance. We shall define below what we mean by pressure and pressure differential in this context.

Our work indicates that a comprehensive theory capable of explaining in detail our experimental observations does not exist. We shall merely put forward

* Paper read at the 27th Annual Meeting of the Society at Dallas on November 11, 1957. Manuscript received by the Editor December 20, 1957.

† Gulf Research and Development Company, Pittsburgh, Pennsylvania.

some working hypotheses which we have found convenient to use. These hypotheses have served to rationalize our data and have enabled us in many instances to predict successfully the outcome of experiments.

We must emphasize the following point. Our experiments are performed in the laboratory on hand specimens. We use equipment designed to measure the transit time through the specimen of signals sufficiently powerful to be observed. We measure, in fact, the first arrivals which are observable on our equipment. Such arrivals are conventionally believed to be associated with longitudinal waves; in most cases, we believe that they are. We have made no quantitative measurements of attenuation; yet it is qualitatively clear to us that the attenuation of energy is a factor in laboratory measurements of velocity and may well be a significant factor in field measurements. We believe this to be true whether the field measurements are made by normal seismic techniques or by continuous velocity loggers. The importance of these observations lies in the following: It cannot be assumed that all laboratory measurements are directly applicable to field problems. In particular, some abnormally low velocities observed in the field, particularly those recorded by present continuous velocity loggers, may result from the equipment used, i.e., the signals observed are later arrivals than might be detected by more sensitive apparatus. A study of the effect of rock structure on the reduction of the strength of transmitted signals is desirable; the use of differential signal strength reduction as a diagnostic tool in field work suggests itself as a practical objective.

It may be noted that rise-times of the signals used to determine velocities varied with the pressure applied and the type of porous medium investigated. In general, the observed frequencies appeared to be of the order of 100–1,000 kc. Wave lengths are thus considerably larger than the grain or pore-sizes of the materials examined.

APPARATUS

Most of the apparatus used has been described in the authors' paper of 1956. Our equipment for measuring transit times has been supplemented by a device capable of both displaying on an oscillograph and photographing signals which arrive after the first received. With the new equipment the velocities of transverse waves may be measured and the presence of reflected energies observed. This equipment was constructed under the supervision of R. D. Wyckoff. This communication, however, deals only with phenomena related to the first arrival of observable pulses.

In this work, as before, all pulses have been generated and recorded by means of ceramic (barium titanate) transducers.

The problem of making velocity measurements on unconsolidated aggregates of particles is a difficult one; in our previous work all measurements on such systems were conducted at atmospheric pressure. Since then we have used the equipment shown in cross-section in Figure 1. The principal difficulty in making

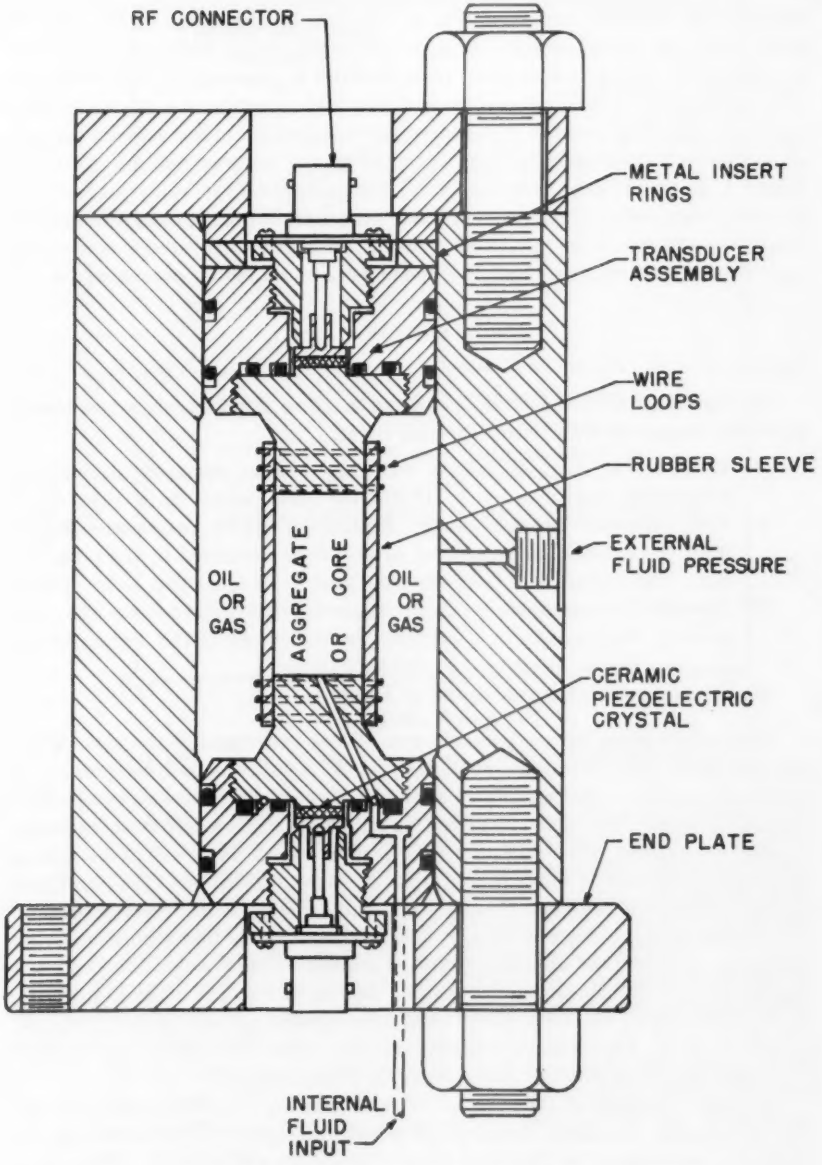


FIG. 1. Velocity differential pressure cell.

conventional velocity measurements on compacted aggregates is the risk of energy being by-passed through material sufficiently strong and rigid to restrain the aggregate during compaction. Such material is generally of high velocity. This problem has been overcome by jacketing the aggregate in a flexible rubber sleeve and applying pressure to the sleeve by means either of low velocity silicone oil (velocity 2,780 ft/sec) or gas contained in the annular volume shown in Figure 1. As will be seen from the figure, it is possible also to apply pressures to the fluid contained in the aggregate. These pressures, of course, cannot be greater than those applied to the jacket. The same apparatus may be used also to apply variable circumferential compacting pressures to consolidated porous media.

RESULTS

General Effect of Pressure on Velocity

We have applied pressure to specimens in three different ways and simultaneously measured the velocity through them:

(1) By jacketing the specimens in thin copper sheet and applying uniform hydrostatic pressures up to 15,000 psi. The jackets have been fitted with brazed-in pressure tubing thereby permitting pressures different from the external to be applied to any fluid contained in the pore volume. The technique is basically that used by Hughes and Kelly (1952).

(2) By jacketing specimens in rubber to prevent evaporative losses and compressing them axially in a hydraulic press. Details of this technique are given in Wyllie, Gregory, and Gardner (1956).

(3) By using the apparatus shown in Figure 1.

The results given by methods (1) and (2) are substantially the same when the specimens used are consolidated. Method (3) may give velocities from 2 to 4 percent lower than the other methods. Figure 2, for example, shows a comparison of data obtained when three cores from the same rock were uniformly compressed, axially compressed, and circumferentially compressed. Figure 3 gives similar data for a sandstone of lower porosity. As we have noted in our 1956 paper and as has been shown in greater detail by Hicks and Berry (1956), what appears to be of primary significance in velocity measurements made under pressure is the difference between the apparent pressure applied to rock solids—the external pressure—and that applied to the fluid in the rock pores. The external pressure, as we shall employ the term, is the total force applied per unit area of the bulk porous medium. The pressure differential is the difference between the external pressure and the hydrostatic pressure on the pore saturant.

A typical example of the effect of external pressure and differential pressure on the velocity of a Berea sandstone is shown in Figure 4. This figure may be compared with Figure 2 of Hicks and Berry (1956). Four characteristic features are:

(a) The velocity increases with increasing differential pressure. The increase

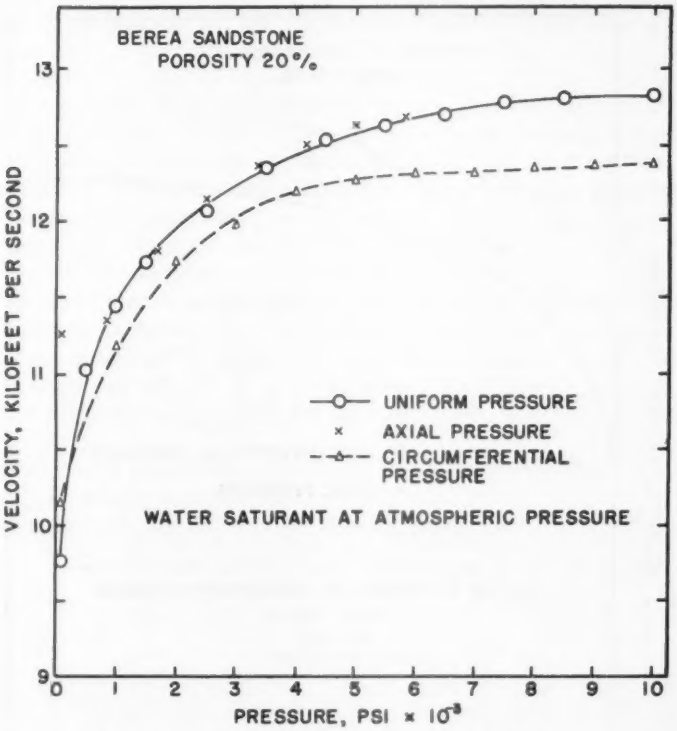


FIG. 2. Results of three methods of compression on different cores from same rock.

is at first rapid but decreases with increasing differential pressure until an approximately constant, terminal velocity is attained.

(b) For zero differential pressure (i.e., identical hydrostatic pressure on both rock material and pore saturant) the velocity at first increases rapidly and then slowly and approximately linearly. The latter characteristic is particularly evident in Figure 2 of Hicks and Berry (1956).

(c) For small differential pressures the behavior is very similar to that at zero differential pressure. At higher differentials the initial velocity rise is not observed.

(d) Different samples of equal porosity from the same rock, or the same sample used repeatedly, may show a variation in measured velocity for a fixed low external pressure. However, the terminal velocity in all these cases is the same.

Data for Figure 4 were obtained using a Berea sandstone which was de-

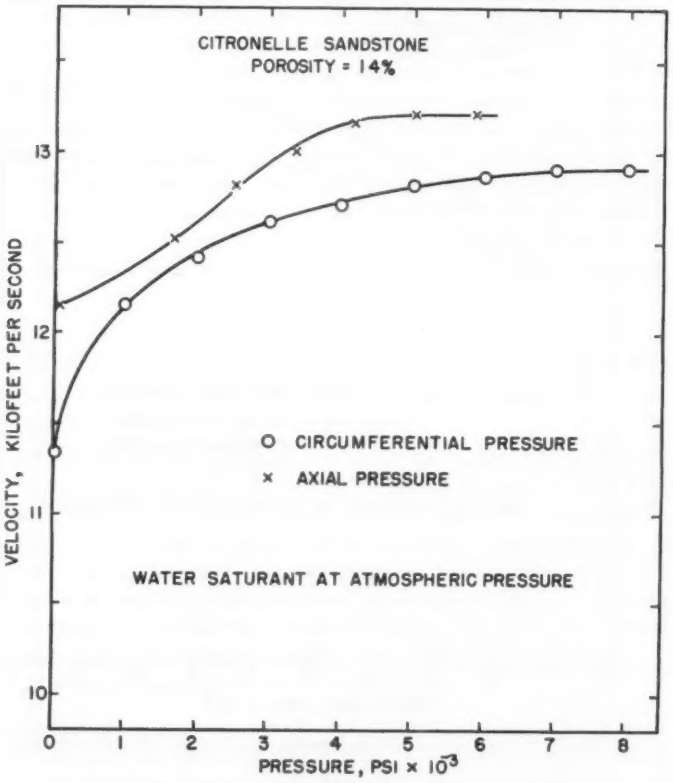


FIG. 3. Results of two methods of compression on same core.

liberately made water-repellent by treatment with a silicone fluid. Such treatment makes it more difficult to saturate a core fully with water. Figure 5 by comparison shows data obtained on a similar Berea sandstone which was naturally preferentially water-wet. Such a core is readily saturated with water. At the maximum differential pressure used the behavior of the two cores is similar and the terminal velocity about the same. At zero differential pressure the behavior is different; in particular, the initial rise in velocity is not observed when a core is preferentially water-wet. It may be noted that the limiting velocity for high external pressure but zero differential pressure is significantly different for the two samples compared with the difference in the velocities observed at high external pressure and high differential pressure.

These results are typical of the differences which arise due to the wetting

properties of the saturant and the use of various samples of the same porosity from the same rock. A Berea sandstone made as preferentially water-wet as possible by firing gave a family of curves similar to Figure 5. This technique is widely used by students of wettability phenomena. The temperature of firing is about 300°C; numerous observations indicate that this treatment does not significantly affect the structure of a Berea sandstone.

The difference in behavior of the Berea cores artificially made preferentially oil- and water-wet is paralleled by certain natural cores. For example, cores from the Citronelle field, Alabama, on recovery exhibit behavior almost identical to that of the silicone-treated Berea core. The same cores when fired or chemically treated to make them water-wet behave in the same manner as water-wet Berea cores. A possible deduction, therefore, is that Citronelle sandstone *in situ* is in part at least preferentially oil-wet. It must be realized, however, that the Citronelle cores were cut with an oil-base drilling mud which may have changed the natural wettability characteristics of the rock (Bobek, Mattax, and Denekas, 1957).

We shall discuss below other experiments which bear on the effect of surface wettability on velocity measurements.

The terminal velocity noted in (a) above appears to be that which is most

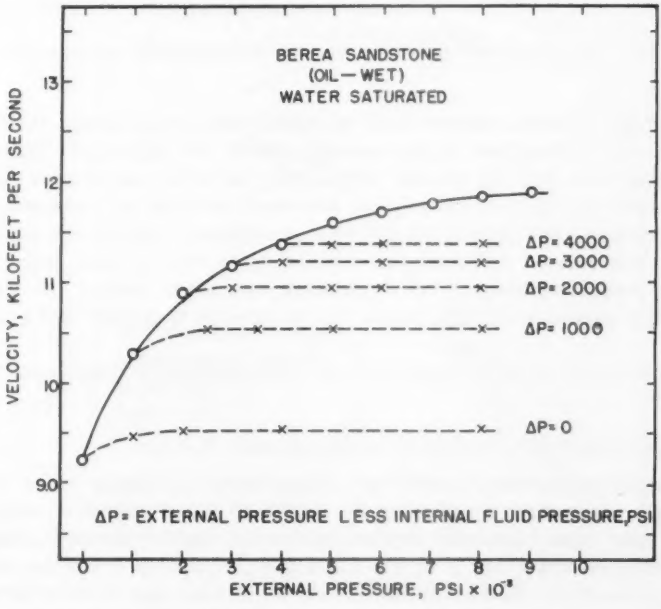


FIG. 4. Velocities through an oil-wet sandstone core under differential pressures.

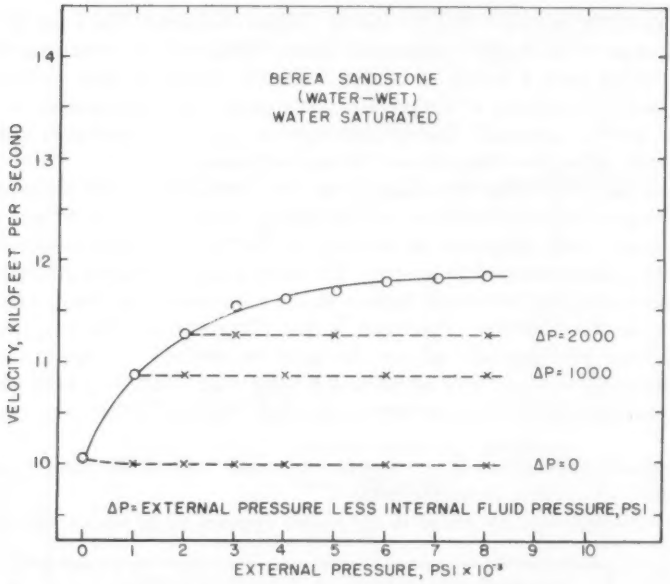


FIG. 5. Velocities through a water-wet sandstone core under differential pressures.

characteristic of measurements made on consolidated porous media. It seems to be relatively independent of the manner in which the differential compacting stress is applied. It is not entirely independent, for in the case of some rocks we have noted that the terminal velocity measured under uniform circumferential compression is 2 to 4 percent lower than that measured under axial compression. Most of our data on well cemented rock specimens were obtained under conditions of axial compression. This is the most convenient method. The external pressure is applied by a rigid piston, and no pressure is applied to the pore saturant.

In the case of unconsolidated or friable rocks simple axial compression cannot be used.

Terminal Velocity of Consolidated Sandstones under Pressure

Velocity measurements made on a wide variety of siliceous rocks are conveniently summarized by plotting the reciprocal of the measured velocity, or transit time, in micro-seconds per foot, as abscissa, and the porosity as ordinate. Data obtained are shown in Figure 6 and refer to rocks of which the majority would normally be classified as sandstones. No attempt was made to divide the sandstones further, e.g., into those cemented with silica and those with lime, nor

was any particular attempt made to insure that the specimens used were homogeneous. All samples were saturated with a brine having a velocity at atmospheric temperature and pressure of 5,000 ft/sec.

In order to extend the range of porosities over which measurements might be made, some rare specimens of siliceous rocks were also obtained. These included samples of radiolarian earth from Barbados (porosity ~73 percent) and samples of tripolite and diatomaceous earth from Missouri and California (porosity 59 percent and 75 percent respectively). The data plotted in Figure 6 are for cores under axial compression. The shape of the experimental curve indicates that terminal velocities were not obtained for the highly porous rocks. The fragile nature of such rocks precludes the application of high directional pressures.

It is possible to estimate the terminal velocities of highly porous rocks by extrapolation when uniform methods of compression are used. A typical extrap-

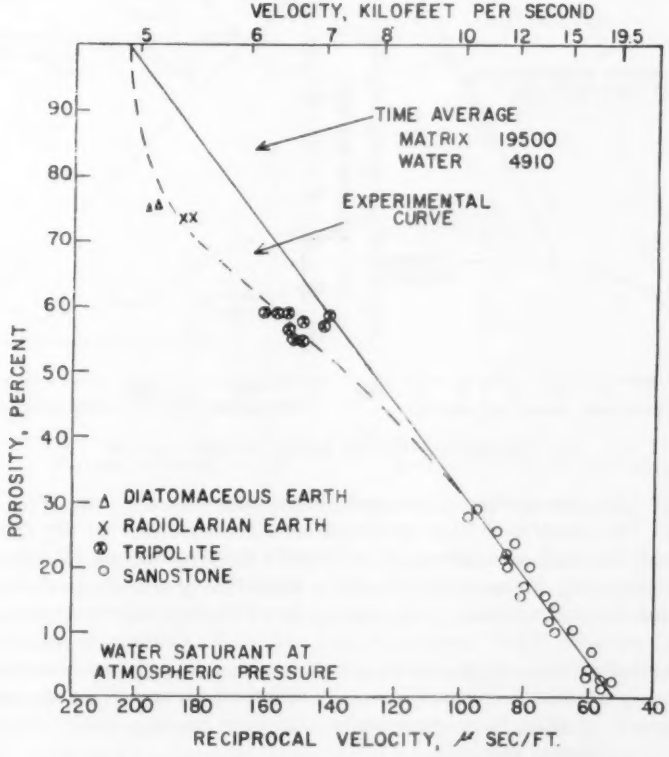


FIG. 6. Velocity versus porosity for silica rocks under directional pressure.

olation is shown on Figures 7 and 8 by a dashed line. The sharp change in velocity which occurs at a pressure of 3,000 psi for radiolarian earth and at 4,000 psi for pumice results from the specimen crushing, with a concomitant radical reduction in porosity. The pumice sample also exhibits anisotropy. In Figure 8 the directions indicated by A and B were orthogonal and the measured velocity showed a considerable change. The radiolarian earth sample was reasonably isotropic.

The terminal velocities in almost all natural sandstones are somewhat greater when saturated with a brine (5,000 ft/sec) than when dry. This difference is not

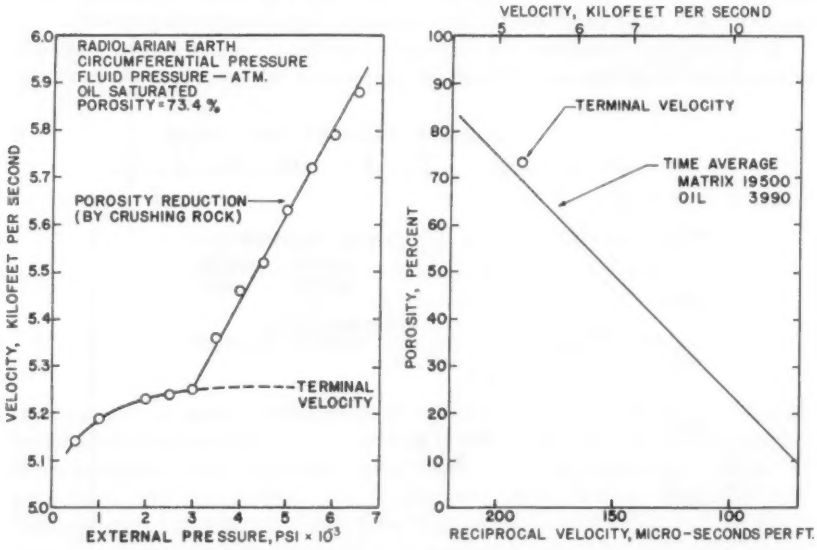


FIG. 7. Extrapolated terminal velocity for radiolarian earth.

observed when measurements are made on samples of pumice and West Texas tripolite. The velocities in these specimens are the same both when dry and when saturated. Synthetic consolidated porous media such as alundum (Norton Company, Worcester, Massachusetts) behave similarly. Synthetic specimens also differ from natural materials in the manner in which their velocity is affected by external pressure. While the velocity in a natural sandstone is in almost every case markedly increased by external pressure, the velocity in an alundum core is relatively unaffected. Figure 9 shows this difference for alundum and sandstone specimens all of which have approximately the same porosity. Each curve corresponds to a different specimen.

Data obtained on sandstones by Hicks and Berry (1956) agree well with those shown on Figure 6. However, the maximum pressure differential used by these

workers was 6,000 psi; it is not certain, therefore, that a terminal velocity was achieved in every case.

Velocity of Unconsolidated Aggregates under Pressure

To measure the velocity in unconsolidated aggregates under various pressures and pressure differentials is not easy. Dry (i.e. air-saturated) aggregates show high signal attenuation. Even through liquid-saturated aggregates the strength of the signals observed is much poorer than through consolidated samples of comparable porosity and length. It is necessary also to insure, when making measurements on unconsolidated aggregates of spheres, that the ratio specimen length/sphere diameter is of the order of five hundred or more. As was shown by the authors in 1956, if this precaution is not observed the velocities measured do

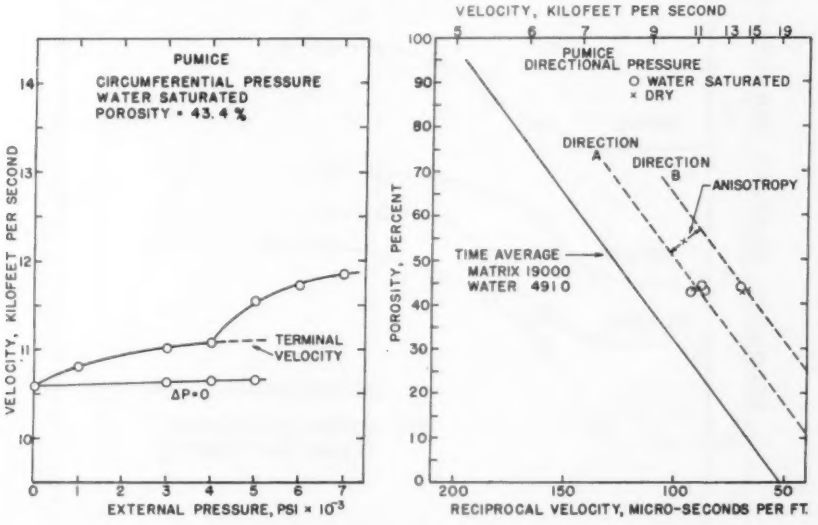


FIG. 8. Extrapolated terminal velocity and anisotropy effect in pumice.

not truly express the properties of the aggregate. In some cases the attenuation of signal strength is so great that it is virtually impossible to insure both an adequate length of specimen for a valid measurement and an adequate strength of signal for an unequivocal observation of transit time.

Reasonably successful measurements have been made on aggregates composed of glass spheres (porosity 37 percent), of a mixture of two sizes of glass spheres (porosity 13 percent), and of Ottawa sand (porosity 35 percent). The measurements made on the aggregate composed of a mixture of spheres of 3 mm and 0.028 mm sizes (approximately 70 percent 3 mm, 30 percent 0.028 mm by volume) are summarized in Figure 10. From this figure it seems that the effect of

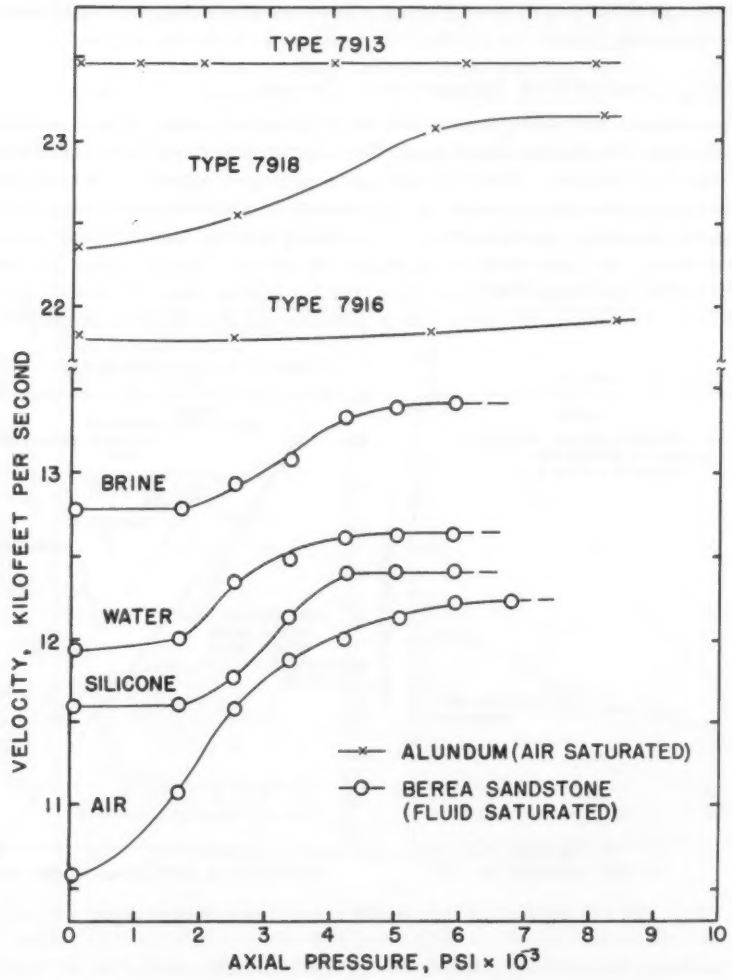


FIG. 9. Comparison of the effects of external pressure on the velocities of alundum and sandstone cores.

frame and differential pressures on an unconsolidated aggregate are qualitatively similar to the effect of pressure on a consolidated rock sample. It appears, however, that a terminal velocity at high differential pressure is not readily attained; indeed, crushing of the glass spheres which comprise the aggregate seems to occur before any limiting velocity is reached.

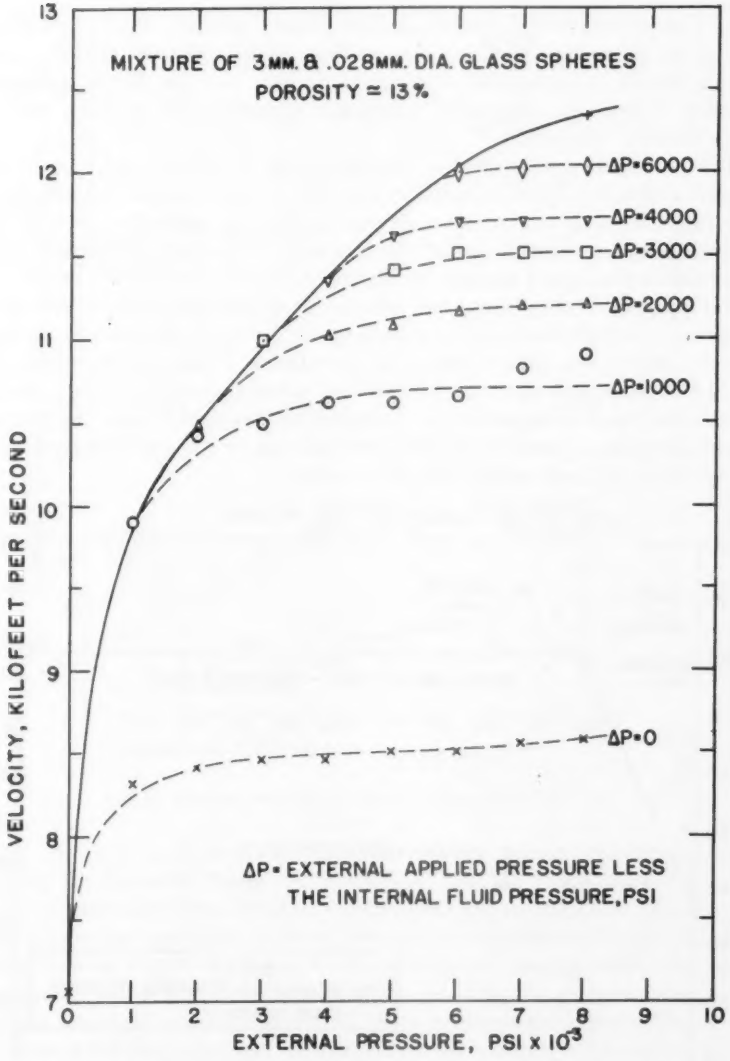


FIG. 10. Velocities through an oil-saturated glass spherical particle aggregate.

Effect of Nature of Fluid Saturant on Terminal Velocity

(1) *Consolidated Media.* We have made a rather extensive investigation of the effect of the nature of a fluid saturant on the terminal velocities of three types of consolidated porous media. The media chosen were (a) Berea sandstone (porosity 20 percent), (b) synthetic alundum (porosity 22.9 percent), and (c) Teflon (porosity 50 percent).

The sandstone was selected as representative of natural sandstones. The material is uniform, readily obtainable, and there is much data in the petroleum literature concerning its properties. Porous alundum is, similarly, a well known synthetic porous medium. It is made by sintering closely sized particles of aluminum oxide with a small amount of binding material. The Teflon core (U. S. Gasket Company, New Jersey) was selected for two reasons. First, the wetting properties of polytetrafluoroethylene are singular. Secondly, and more important, it is one of the few consolidated porous materials obtainable for which the velocity of the matrix material (4,400 ft/sec) is less than that of many liquids. Experimental work on natural rocks is severely handicapped because the velocity of such minerals as quartz (c. 19,500 ft/sec) exceeds by a factor of at least three the velocities of liquids usable as pore saturants.

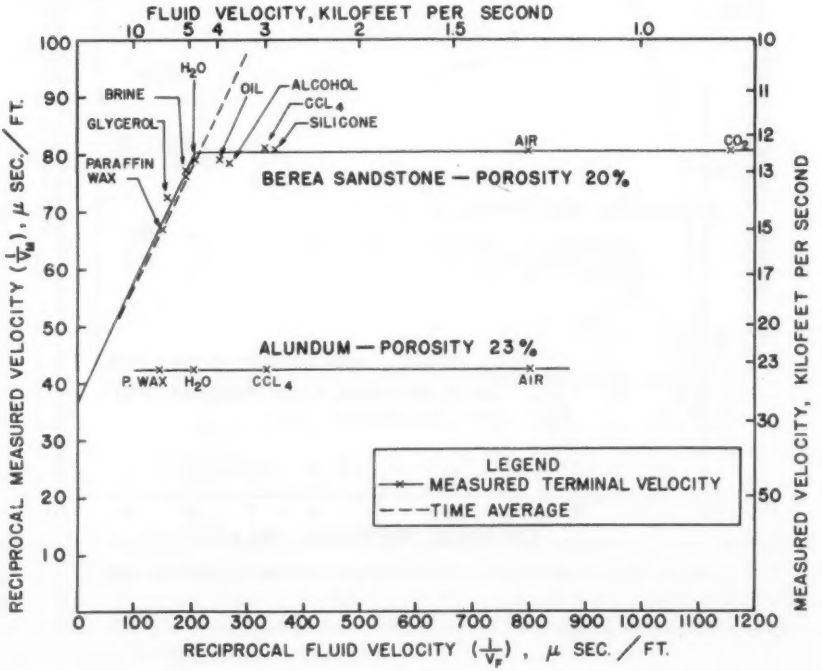


FIG. 11. Effect of saturant on terminal velocities of Berea sandstone and alundum cores.

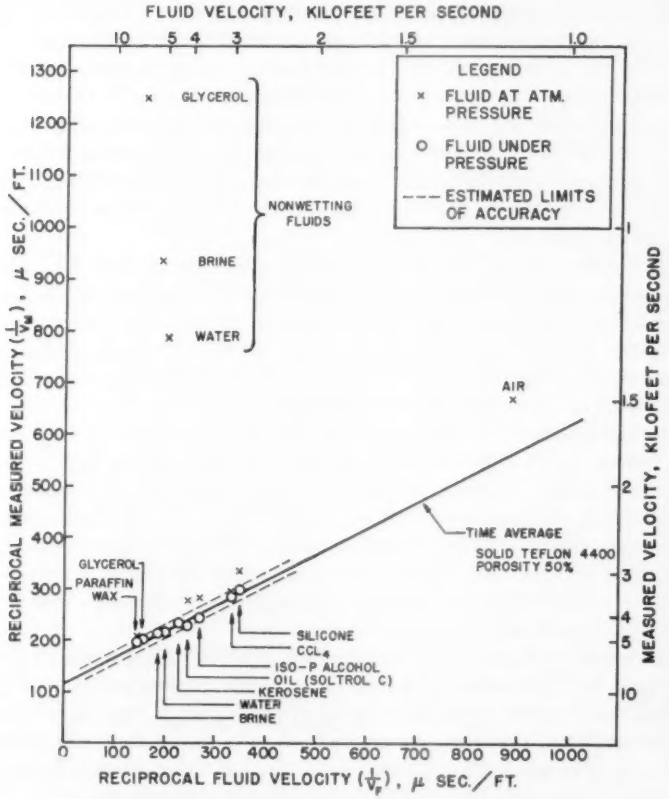


FIG. 12. Effect of saturants on velocities of porous Teflon cores.

Data obtained on the Berea and alundum cores are conveniently summarized in Figure 11; Figure 12 shows the comparable data for Teflon cores. On both figures the reciprocal of the terminal velocity observed through a saturated core is plotted as ordinate with the reciprocal velocity of the saturating fluid as abscissa.

The data on Figure 12 require some comment and amplification. The very low velocities for Teflon cores containing the polar liquids glycerol, brine, and water are measured when the saturants are at atmospheric pressure. Owing to the nature of the Teflon surface, polar liquids do not spontaneously wet the cores, and saturations exceeding about 50 percent pore volume cannot be obtained unless the fluids are subjected to pressure. When pressure is applied to these liquids so as to force them into the pores of the Teflon core and saturations approaching 100 percent are obtained, the measured velocity increases greatly (and, correspondingly, the reciprocal velocities decrease).

It may also be observed that the measured velocities in these non-wetting fluids at atmospheric pressure are actually less than the velocity when the core is filled with air. This we believe is a clear example of signal reduction resulting from energy absorbed by globules of liquids present in the pores. (Even at about 50 percent saturation the polar liquids do not seem to form a continuous phase.) Owing to the presence of the globules, energy which otherwise would travel through the matrix material is lost. Thus the effect of the non-wetting fluids is to diminish the amplitude of the first arrival to such an extent that we observe a low and anomalous velocity.

With liquids such as silicone oil, hydrocarbon oil (Soltrol C), kerosene, molten paraffin wax, and isopropyl alcohol, difficulties in saturating the cores are minor or do not arise. Increasing the fluid pressure changes the measured velocity only slightly. It is not possible, owing to their plastic nature, to apply large external pressures to high-porosity Teflon cores. Thus the data shown on Figure 12 were obtained at rather low external pressures.

The implications of the data shown in Figures 11 and 12 will be considered further below. It will suffice to note here that the velocity in a Berea sandstone appears to be a function of the velocity of the saturating fluid only if the velocity in the saturant exceeds that of water (4,900 ft/sec). For fluid saturants with velocities less than 4,900 ft/sec the measured velocity is approximately constant. It may be noted that oil- and alcohol-saturated cores have velocities which appear to be slightly greater than the same cores saturated with carbon tetrachloride, silicone oil, air, or when evacuated.

No saturant was found which would affect the velocity in a synthetic alundum core (Figure 11). The velocity in such cores is usually identical whether dry or saturated, but in some cases the velocity in dry alundum appears greater than in water-saturated alundum. By contrast, it was found that the velocity in Teflon cores was markedly increased over the dry value when saturated with any of the liquids used. The quality of the arrivals observed was also a function of the saturant. For paraffin wax, glycerol, brine, oil, carbon tetrachloride, and isopropyl alcohol, the quality of the arrivals varied between good and excellent. For water, kerosene, and silicone oil, the first arrivals were more equivocal and a subjective element entered the determinations. Plotted on Figure 12 are the most likely values of reciprocal velocity. It must be understood, however, that the first arrival did not appear as a very sharp break in the trace on the oscilloscope screen; the dotted lines indicate the limits of uncertainty introduced by this ambiguity.

(2) *Unconsolidated Media.* The velocities at differential pressures of 9,000 psi were measured through two unconsolidated porous aggregates when these were saturated with various fluids. The aggregates selected were (a) glass spheres of average diameter 0.051 mm (porosity 37 percent) and (b) Ottawa sand, average diameter about 0.65 mm (porosity 35 percent). At a pressure differential of 9,000 psi the velocity through the aggregates appeared to be approaching, although not to have reached, a terminal value.

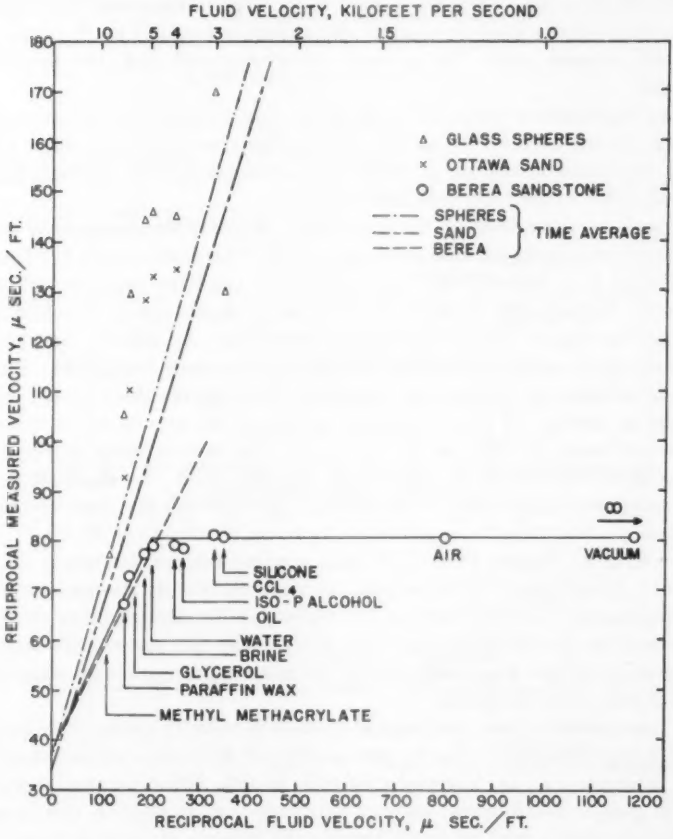


FIG. 13. Effect of saturants on consolidated and unconsolidated materials.

Figure 13 shows the data obtained. As before, the reciprocal velocity through the fluid-saturated aggregate is plotted as ordinate and the reciprocal of the fluid velocity as abscissa. On the figure is also shown the velocity previously found (Wyllie, Gregory, and Gardner, 1956) for a packing of uniform spheres of 37 percent porosity saturated with methyl methacrylate plastic. The interpretation of these data is considered later.

The Effect of Partial Fluid Saturations on Limiting Velocities in Sandstones

Wyllie, Gregory, and Gardner (1956) showed how the velocity through saturated sandstone cores was affected by varying the initial water saturations. In the work referred to, cores initially water-saturated were progressively desat-

urated with oil or air. While the variations in velocity observed depended upon the porosities of the sandstones used, differences of as much as 30 percent were measured between cores 100 percent water-saturated and 100 percent air-saturated.

These experiments were conducted on cores at atmospheric pressure; as such they may be considered atypical of rocks *in situ*. The experiments have been repeated with cores subjected to differential pressures sufficiently high to insure the attainment of terminal velocities.

Typical data obtained by the progressive capillary desaturation of a Berea sandstone core are shown in Figures 14 and 15. The desaturation for Figure 14 was effected in a conventional "restored state" capillary pressure cell and involved the displacement of water by "Soltrol C" hydrocarbon oil while the desaturation for Figure 15 was achieved by evaporation. All velocity measurements were made under axial compression, the confining pressure being 4,000–5,000 psi, with the saturant at atmospheric pressure. Both figures show that a velocity decrease of between 2 and 4 percent occurs as the saturation changes from 100 percent water to 100 percent oil or air. (The measurement at 100 percent oil-saturation was made by extracting the core after the attainment of an irreducible water-saturation in the capillary pressure cell and then resaturating it with oil.)

The data of Figures 14 and 15 thus confirm the measurements shown in Figure 11. In addition they reveal that there are no velocity anomalies at saturations intermediate between 100 percent water and 100 percent oil or air. Experiments made on synthetic alundum cores also showed that the velocity under high differential pressures was unaffected by the relative proportions of water and oil or water and gas in the pores.

In fact, our data show that marked changes in velocity are unlikely to accompany the replacement of brine by gas or oil in oil field rocks subjected to differential pressures, i.e., as they probably exist *in situ*. While we shall discuss this point in greater detail below, we may note here that, in essence, this important practical conclusion may be drawn because the velocity of the rock matrix material is relatively so high by comparison with the velocities of gas, oil, or water. If dry rocks had velocities comparable with our synthetic Teflon cores, a very different conclusion could be drawn. For Teflon cores, the velocities gas-filled, oil-filled, and brine-filled would be markedly different. Further, we have observed the following fact. For a Teflon core 50 percent saturated with a wetting liquid and 50 percent gas-saturated, the velocity observed is quite close to the velocity when 100 percent liquid-saturated. When the same core is 50 percent gas-saturated and 50 percent saturated with a non-wetting liquid, the velocity observed is less than the velocity dry. (See Figure 12). This result obtains even when the velocities of the wetting and non-wetting liquids are virtually identical. Thus the measured velocity in a Teflon core is more affected by the wetting properties of a liquid which partially saturates it than it is by the velocity in the liquid saturant itself.

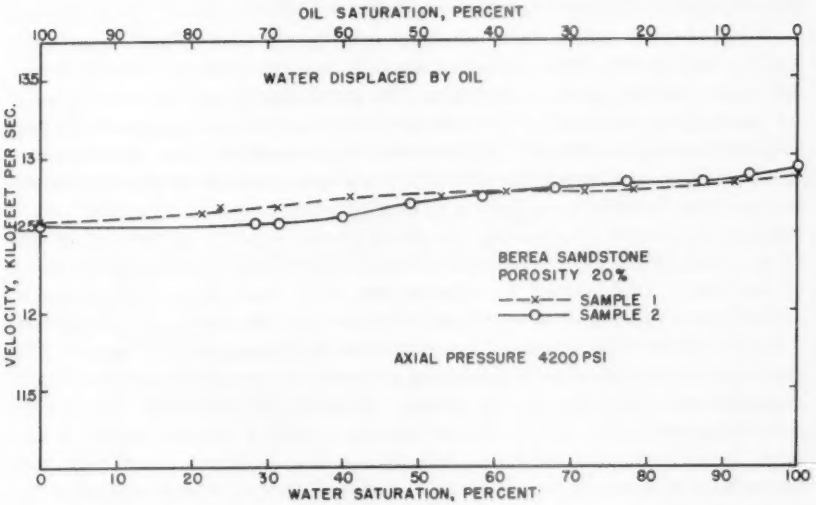


FIG. 14. Velocity as a function of oil and water saturation at a constant axial pressure.

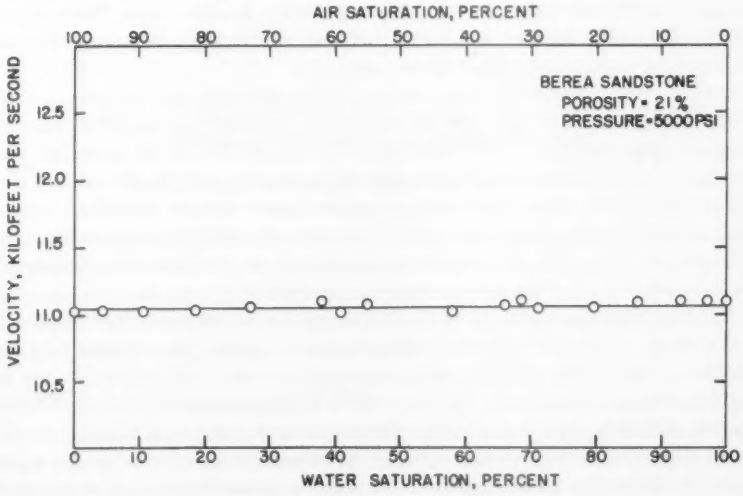


FIG. 15. Velocity as a function of water and air saturation in sandstone core at constant axial pressure.

The Influence of Vugs and Fractures in Rocks on Velocity

Figure 6 shows clearly that, for sandstones, the terminal velocity is a strong function of porosity. The question arises: Is velocity through limestones and dolomites similarly porosity-dependent? In particular, is the velocity through carbonate rocks predictable when the porosity is not of the intergranular type, as in sandstones, but is largely of the so-called intermediate type, i.e., the result of natural fracturing or solution of the primary rock structure by ground waters? Intermediate porosity in carbonate rocks is of prime economic importance since many of the largest oil reservoirs owe their storage capacity to porosity of this kind. Characteristically intermediate porosity differs from intergranular porosity in two ways. Vugs formed by solution are often much larger than pores in homogeneous rocks such as sandstone; they are also less uniformly distributed. These factors have for long posed a considerable problem to the core analyst. The typical heterogeneity of rocks possessing intermediate porosity makes it virtually impossible to obtain samples by present coring techniques which can be considered representative. In continuous velocity logging a similar problem is evident. Here the transmitted energy follows a path of minimum travel time from transmitter to receiver. Unless the path followed is truly representative of the environment penetrated by the borehole no obvious correspondence between velocity and porosity, as normally measured, will be evident. This conclusion must hold irrespective of the existence of any systematic relationship between porosity and velocity.

There are thus good reasons for anticipating that in rocks possessing intermediate porosity any relationship between porosity, as conventionally measured, and velocity will be far from evident. Since proof of this supposition was desirable the following experiments were carried out.

Outcrop specimens of Nittany dolomite were obtained near Bellefonte, Pennsylvania. The rock was light grey in color and contained tan clayey streaks and scattered vugs ranging in size from about 0.1 mm to 20 mm in diameter. Since the vugs appeared to be caused primarily by the leaching action of surface waters, it was possible to select samples for measurement which contained vugs in variable numbers and sizes. By careful selection samples of significant size could be found which contained virtually no vugs at all. In these samples the porosity was very small and of the homogeneous intercrystalline type.

Velocity measurements made on the samples are summarized in Figure 16. In this figure reciprocal velocity is plotted against porosity in our usual manner. Samples in which the porosity was apparently entirely intercrystalline are distinguished from those in which it was in part intercrystalline also but principally vugular. It will be seen that the velocities of the specimens with vugular porosity are all slightly less than those with purely intercrystalline porosity. To a large extent, however, the measurements show that the velocities of vugular specimens are independent of porosity. Two measurements made on slightly fractured

samples are also shown in Figure 16. These velocities are appreciably smaller even than those characteristic of vugular specimens.

In general, the conclusion to be drawn from Figure 16 is the following. The velocity through vugular specimens and, to a lesser extent fractured ones, does not depend upon the total porosity. It seems to depend, principally, upon the velocity of the rock matrix material with its attendant intercrystalline porosity. Thus the transmitted energy seems to follow the path of maximum velocity; in

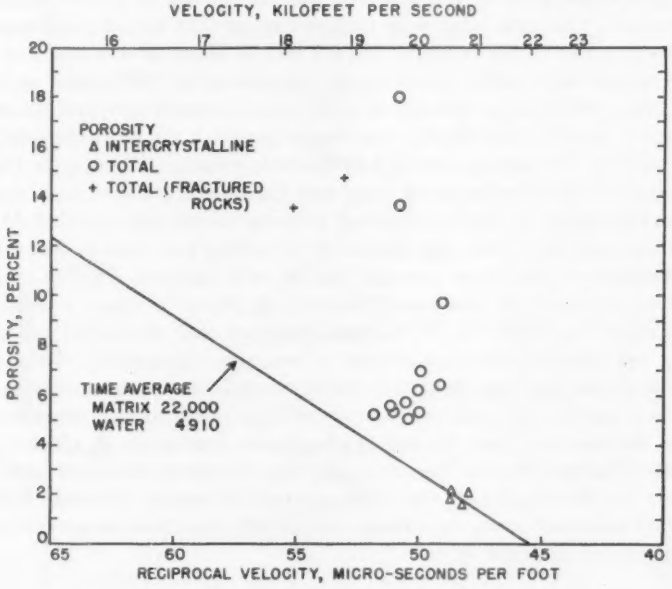


FIG. 16. Velocity as a function of porosity for a dolomite rock.

so doing it largely by-passes the vugs and fractures by following a path of minimum travel time in the homogeneous matrix of the rock. It should be noted that fractures perpendicular to energy paths may not be by-passed but may give lower apparent velocity due to attenuation of signal. Air-filled fractures, in particular, cause a large attenuation of signal strength.

Comparison of Laboratory and Field Data

In measuring velocities through porous media, it is always possible that dispersion effects may be encountered. We have never been able to detect evidence of dispersion in our laboratory studies, but this cannot be considered to prove that dispersion can always be ignored. We again note that the apparent wave

lengths of transmitted signals were in all cases much larger than the pores in the media used. From a more practical standpoint we were interested in ascertaining whether our laboratory data could normally be used to interpret continuous velocity logs. In order to check this point the following experiment was carried out.

Cores of 3.5 inches in diameter were taken from two separate 100-ft sections of a West Texas well. A Seismograph Service Corporation continuous velocity log using a single detector and a source-detector spacing of 5.92 ft was run in the same well. The cores taken were broken into one-foot sections, and from each section a plug two inches in length and 0.9 inch in diameter was cut. The plugs were extracted with carbon tetrachloride, oven-dried at 110°C, and saturated with a brine which had a velocity of 5,300 ft/sec at room temperature and atmospheric pressure. This velocity was chosen to match the probable velocity in mud filtrate at the temperature and hydrostatic pressure obtaining in the well at the depth cored. The saturated plugs were then subjected to an axial external pressure equivalent to their overburden pressure minus hydrostatic fluid pressure *in situ*, and their velocities measured. A running 6-ft average was made of the measurements and these averages plotted as a function of depth to give a laboratory version of the continuous velocity log. Figure 17 shows a comparison of a synthetic log made in the manner described and the actual continuous velocity log recorded. The comparison is favorable, particularly if the rather small size of the plugs measured is borne in mind. It seems not unreasonable to conclude from this and similar evidence we have obtained that measurements made in the laboratory may be used as a legitimate foundation on which to build methods of interpreting continuous velocity logs. However, we would again draw attention to the possibility that instrumental differences between field and laboratory equipment may contribute to apparent discrepancies between velocities logged and observed by us.

SPECULATIVE INTERPRETATION

In all our experiments, the transit time for the arrival of a detectable signal has been measured. At any instant, therefore, we can imagine the rock divided in two parts, one where a detectable signal has arrived at all points, the other where a detectable signal has not arrived, and what we measure, in fact, is the velocity with which the surface of separation between the two regions travels. That this surface moves with constant velocity, provided the specimen is sufficiently long, has been checked within the limits of experimental error.

The theoretical account of the experiments, which we advance tentatively, deals with the motion of this surface and connects it with the physical properties of the rock and saturating fluids. The signal velocity through fluid alone, the signal velocity through solid rock alone, the acoustic coupling between the fluid and the rock, and the geometrical structure of the porous rock are the factors which enter the theory. We have found no evidence that the wave lengths in the

transmitted pulse play a significant part, but we have not thoroughly tested this possibility.

We would note, however, that we are not unaware of certain obvious objections to our speculations. Thus, the concept of a pulse whose principal Fourier components have apparent wave lengths several orders of magnitude greater than

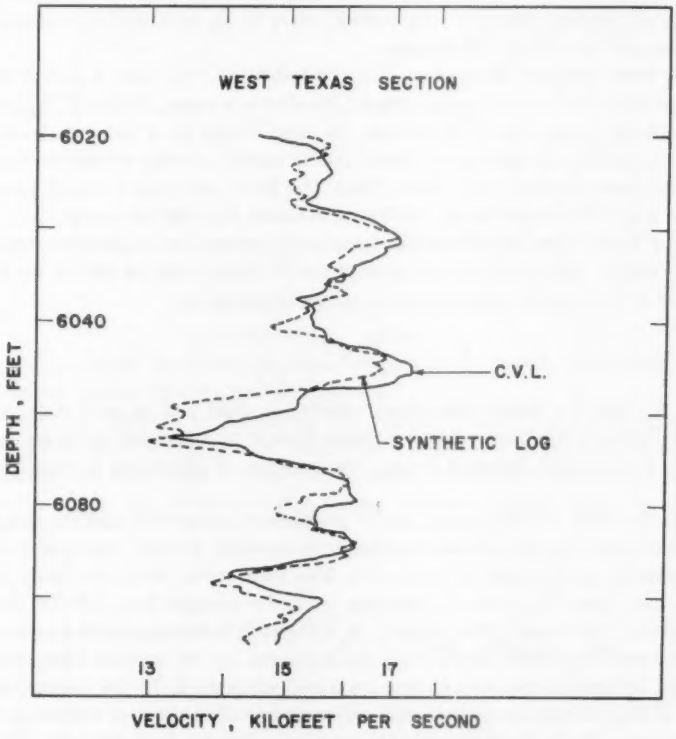


FIG. 17. Comparison of field c.v.l. with synthetic laboratory log.

the characteristic dimensions in our media, and yet able to follow essentially microscopic paths, is naturally repugnant to the classical physicist. We can only assert that, experimentally, we have found such a concept, anomalous as it may seem, singularly fruitful.

For a simple starting point, let us assume that the acoustic coupling between fluid and rock is perfect, that is, the reflection coefficient for a signal passing from one to the other is zero. This could be achieved in one or two cases by choosing suitable fluids. In general, however, the reflection coefficient is not zero, so

we are considering here an ideal situation. The modification introduced by imperfect coupling will be discussed later.

In this ideal case, the surface of separation at the front of the advancing signal may be regarded as a surface of discontinuity, and, as is well known from Love's work (1944) on the general theory of elastic vibrations, its motion may be described by Fermat's principle of least time. The ray velocity is equal to the velocity of propagation of a longitudinal wave in an unbounded medium, that is, the signal velocity of the medium.

The principle may be expressed in the following way. Let A and B be any two points in the body at unit straight line distance apart, and let C denote any curve joining them. Let $T(C)$ denote the time taken by a point to traverse C having a velocity at each point equal to the signal velocity of the medium immediately surrounding that point. Then, the time taken by a signal generated at A to reach B is equal to the minimum value of $T(C)$ for all curves C.

Let x denote the fraction of the length of C which lies in the pore space and let $r(x)$ denote the length of the *shortest* curves which may be drawn for a fixed value of x. The transit time for these curves is given by

$$T = \frac{xr(x)}{V_F} + \frac{(1-x)r(x)}{V_R} \tag{1}$$

where V_F and V_R denote the signal velocity in fluid and in solid rock, respectively. The time taken by a signal to travel from A to B is obtained by minimizing T and, because AB has unit length, the velocity of the signal is equal then to $1/T$.

The function of $r(x)$ has a purely geometrical character and its shape distinguishes one type of porous structure from another. Certain features, however, are common for all types of structures. The least value which $r(x)$ may have is unity, and then the curve C coincides with the straight line AB. In this case the fraction x is equal to the porosity, ϕ, if the rock is homogeneous and isotropic. If both rock and fluid form continuous phases, as we assume here, then the greatest values for $r(x)$ occur when $x=0$ and when $x=1$. In the former case the curve C lies entirely in the rock and $r(0)$ may be called the rock sinuosity; in the latter case C lies in the fluid and $r(1)$ may be called the fluid sinuosity. The general character of the structure function $r(x)$ is illustrated by the solid curve in Figure 18.

Assuming a suitable polynomial expression for $r(x)$, it is a routine matter to calculate the value of x for which T, given by equation (1), is a minimum. Three cases arise depending on the relative sizes of V_F and V_R: (1) the minimum is given by $x=0$; (2) the minimum is given by $x=1$; (3) the minimum is given by an intermediate value of x. Correspondingly, we get three formulas for the signal velocity, V_M, through the porous rock. These are illustrated in Figure 19, where $1/V_M$ is plotted against $1/V_F$ for fixed V_R. For small V_F, $x=0$, and the signal passes through the rock and not the fluid. For very large V_F, $x=1$, and the signal path lies entirely in the fluid. For intermediate values of V_F, we get a

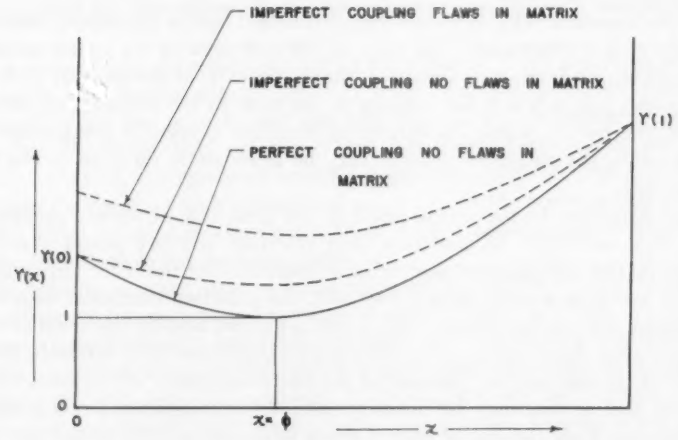


FIG. 18. Sketch of structure function $r(x)$.

curve, depending in detail on the exact shape of $r(x)$, which is tangent to the time-average line at $V_F = V_R$ and lies below it.

In practical cases the rock velocity V_R is usually much larger than any available fluid velocity V_F. Hence only part of the curves in Figure 19 are of possible significance. We may expect, however, to observe a distinct break at a certain critical fluid velocity. With saturants having a lower velocity than this critical

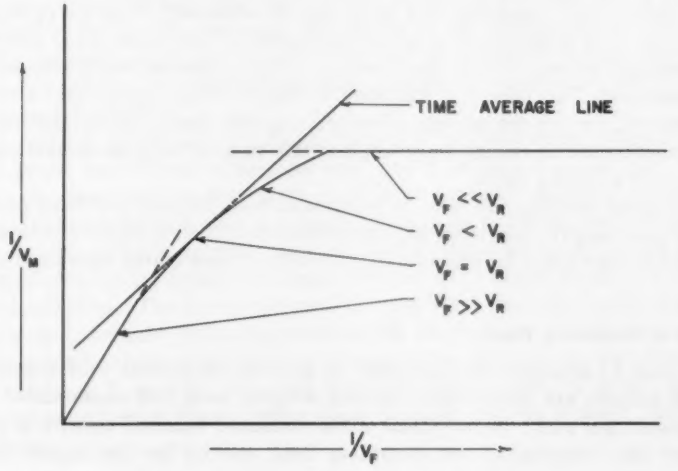


FIG. 19. Theoretical relation between measured velocity and fluid velocity for perfect coupling.

value, the measured velocity should remain constant (and is the velocity measured when the rock is evacuated). The ratio of the rock velocity V_R to this measured constant velocity is the rock sinuosity, that is, the ratio of the shortest path joining any two points which lies entirely in the rock to the straight line distance between the points. When the saturating fluid has a velocity greater than the critical value, the measured velocity may be expected to lie close to the time-average line.

This describes the theoretical result in the ideal case of perfect coupling between rock and fluid. At moderate fluid velocities any ray passes alternately through matrix and saturant, and we have assumed that the reflection coefficient at every interface is zero. In fact, however, the reflection coefficient depends on the difference in the impedances $\rho_F V_F$ and $\rho_R V_R$ and also on the angle at which the ray strikes the interface. The effect of this impedance is to diminish the amplitude of the first arrival. Because of the finite sensitivity of the detecting device, the first arrival may be imperceptible. What is measured is a somewhat later arrival. Thus the loss of energy tends to counteract the divergence of the curved segment in Figure 19 from the time-average line. This may account for the remarkably close agreement between the measured velocities for a Berea sandstone and the time-average values as depicted in Figure 13.

The loss of signal strength discussed here depends partly on the different impedances of the rock and fluid and partly on the geometrical structure of the porous medium. Let us suppose, now, that we have a structure for which the reduction of signal strength due to imperfect coupling is important, as, we believe, is the case for most unconsolidated sands. The function $r(x)$ must be modified. The signal which reaches B along a particular path C may pass undetected and hence only a later signal arriving by C may be observed. Thus the path length associated with a particular value of x is increased. The paths lying entirely in the rock and entirely in the fluid cause no attenuation and hence $r(0)$ and $r(1)$ are unaltered. This change is indicated in Figure 18 by the dotted curve. Unfortunately, we can see no way of calculating this change quantitatively. The general effect of this change, however, is merely to alter the intermediate segment of the $1/V_M - 1/V_F$ curve.

One final modification may be mentioned here. If there are flaws or cracks in the rock matrix these may cause additional reduction in signal strength. This implies a larger value for $r(0)$ than would occur if these cracks were filled in with rock.

Effect of Saturating Fluid

Figure 13 illustrates a comparison of some of these ideas with observation. Three samples are shown: glass spheres, Ottawa sand, and consolidated Berea sandstone. For each, the reciprocal of the measured terminal velocity is plotted against the reciprocal of the saturating fluid velocity for the highest possible

external pressure. For reference, the time-average line for each sample is also shown.

It is evident that the measurements for consolidated Berea sandstone support this theory. The leading edge of the trace on the oscilloscope screen caused by the arrival of the first pulse is clear and unambiguous and the measurements reproducible. When the fluid velocity is less than about 5,000 ft/sec, the signal velocity for water, the measured velocity is sensibly constant. This implies, according to the theory, a rock sinuosity of about 1.6. In the presence of a saturating fluid with a velocity greater than 5,000 ft/sec the measured velocity increases, and the time-average line is closely followed.

The velocity through various unconsolidated aggregates was measured, but the results were less easy to understand and more difficult to obtain. The fastest observed signal frequently has a low amplitude and a relatively long rise time. This makes transit times through such materials inherently difficult to measure with an acceptable degree of accuracy. Increasing the external pressure on the sample resolves some of the ambiguity but a clear terminal velocity is less apparent than for consolidated rock, as may be seen by comparing Figures 10 and 5. In Figure 13, the estimated terminal velocities for the unconsolidated samples are plotted for those saturants which appeared to give a terminal velocity. It may be noted that no point is given for a dry air-filled aggregate. Using the cell shown in Figure 1 with nitrogen gas surrounding an aggregate composed of dry glass spheres, the measured velocities at pressures of 500 and 1,500 psi were 3,500 and 4,000 ft/sec respectively. Due to the limitations of the apparatus, it was not possible to increase the pressure above 1,500 psi in this case. Hence, no estimate of a terminal velocity could be made.

It may be noted that when the saturant is methyl methacrylate or paraffin wax, which, being solid, increases the rigidity of the aggregate, the measured velocity lies close to the time average. The gradual decrease in measured velocity as the paraffin wax becomes molten with increase in temperature has been reported by Iida (1939).

To test the theory further, measurements were made on an alundum core and a Teflon core. For alundum, the solid matrix velocity V_R is at least 29,700 ft/sec; this measurement was made on a hand specimen of emery (aluminum oxide). It is large enough that the theory predicts no available fluid will change the measured velocity; in every case the first arrival travels through the solid matrix. Teflon, on the other hand, has a very low solid matrix velocity, V_R being about 4,400 ft/sec. The theory now predicts that every fluid affects the measured velocity and, because Teflon is consolidated, the velocity should be approximately given by the time average. In all cases these expectations were borne out by experiment. It may be remarked, however, that the quality of the first arrivals for some fluid-saturated Teflon cores was poor. Figures 11 and 12 illustrate the results.

Effect of Pressures

To explain the large effect which pressure has on velocity, we advance the hypothesis that for natural porous media the rock matrix has numerous cracks and flaws. The effect of external pressure is to close these cracks. If, however, the fluid pressure is increased along with the external pressure so that the differential pressure remains constant, then the matrix material is subjected to an additional uniform hydrostatic pressure and the cracks are not closed.

Thus at high differential pressures the rock matrix is relatively homogeneous, and a signal which travels through it suffers little loss of energy because of flaws. Due to the high velocity in solid rock relative to water or air, this signal may constitute the major energy component of the first arrival. If so, the water or air content of the core is relatively unimportant, and the velocity depends only on the value of the differential pressure. This is exemplified in Figures 4 and 5, where the behavior of the cores at high differential pressures is independent of the wettability.

As the differential pressure is lowered and cracks become more numerous, the signal which travels primarily through the rock matrix suffers additional energy losses and its apparent transit time is increased. This reduction in velocity makes it possible for the energy through the fluid path to exert a greater influence on the over-all rock velocity. Thus at lower differential pressures the velocity in the saturant may become increasingly relevant. Under these circumstances the wettability of the rock influences the measured velocity. The presence of air increases the reflection coefficient for a signal passing from rock to saturant and lowers the observed velocity. Increasing the fluid pressure, holding the differential pressure constant, reduces the volume of air and hence causes an increase in velocity. In this way the families of curves in Figures 4 and 5 may be reasonably explained.

Alundum cores show little change in velocity due to external pressure. This we attribute to absence of flaws in the matrix material of this synthetic rock. To test this hypothesis several cores were subjected to tension until they broke. This, we believed, might induce cracks in the material. Where before being stressed in this manner a core showed a change of less than 100 ft/sec due to a pressure increase of 10^2 psi, the same core after being fractured became more sensitive to pressure and showed a change of up to 700 ft/sec.

The measured velocities plotted in Figure 11 are those obtained for high external pressures. Under these conditions the cracks in the matrix are closed and the simplified theory may be expected to apply.

The conjectured existence of cracks in natural rock matrices is further upheld by the lower terminal velocities obtained when a consolidated core is subjected to a circumferential pressure, as in the differential pressure cell, than when it is axially stressed. In the latter case cracks perpendicular to the direction of the signal are closed, whereas in the former case these may not be closed. Thus the

length of the path which lies in the rock material is reduced by a greater amount by the axial stress.

Stress-Strain Relationships

If the primary effect of pressure, as far as velocity measurements are concerned, is to open or close cracks in the matrix material, then little correlation may be expected between velocity and the elastic parameters of the medium, except perhaps at high external pressure when the cracks are closed. To investigate this point some exploratory tests were made. Strain gages were cemented

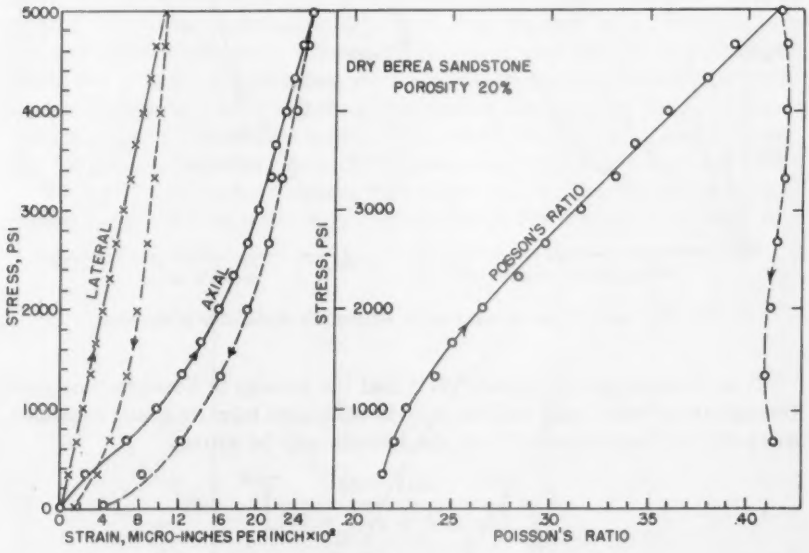


FIG. 20. Stress-strain relationships in Berea sandstone.

to a cylindrical core parallel and perpendicular to its axis. A compressive force was applied in the direction of the axis and the signal velocity in this direction measured. A maximum pressure of about 5,000 psi was used for the sample referred to here, which is below the pressure at which the rock starts to fail.

Figure 20 shows a graph of axial and lateral strain against stress for a dry Berea sandstone. From this, Poisson's ratio may be calculated and is shown in the same figure. The stress-strain relation shows a considerable dependence on the nature of the saturating fluid. For example, at 5,000 psi the axial strain in microinches per inch was 2,600 for air, 2,880 for oil, 3,380 for silicone and 3,480 for water, the pressure in the fluid being atmospheric. The relationship for a dry and water-saturated sandstone is shown in Figure 21.

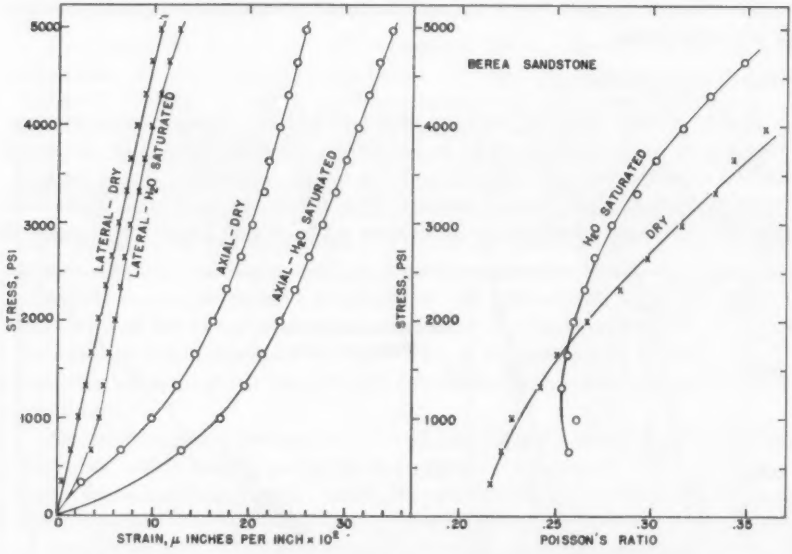


FIG. 21. Effect of water saturant on the stress-strain relationship in sandstone.

It has been suggested (Wood, 1941) that the velocity of a longitudinal wave through an extended solid medium may be calculated from its elastic constants. For a dry rock, saturated with air, the formula may be written

$$V = \left[\frac{E(1-\sigma)}{(\rho/g)(1+\sigma)(1-2\sigma)}\right]^{1/2} \tag{2}$$

where

V = longitudinal velocity, ft/sec
E = Young's modulus, psf $\times 10^6$
σ = Poisson's ratio
ρ = bulk density, pcf (average of rock and saturant)
g = acceleration due to gravity, ft/sec^2.

The velocity computed from the data illustrated in Figure 20 by means of equation (2) is plotted against the stress in Figure 22. For comparison the measured velocity is also plotted. At 2,000 psi there is a difference between the computed and measured velocity of almost 4,000 ft/sec or about 30 percent of the measured velocity.

As a check, the same procedure was followed for a solid cylinder of brass. The measured velocity was 14,200 ft/sec and the calculated 13,300 ft/sec.

In a similar way the velocity through a dry alundum core was calculated to be 21,500 ft/sec, and it was directly measured as 23,000 ft/sec.

Further work on the stress-strain relations is planned for the future. While there does not appear to be a direct relation with the velocity of sound, it is clearly of importance for a thorough understanding of the structure of porous media.

Effect of Wettability

The theory suggests that poor coupling between rock and fluid, with consequent weakening of the transmitted signal, may give rise to low anomalous velocities. For example, a rock with a preferentially oil-wet surface when saturated with water at atmospheric pressure may be regarded as having a large effective acoustic impedance differential; the water does not penetrate the finest cracks and pendular spaces across which the first arrival would travel, and reflections at the gas-solid interfaces are almost perfect. On the other hand, the better wetting properties of oil allow it to establish a good contact with the rock surface, and the acoustic impedance difference between rock and fluid is relatively small.

To test these ideas several cores were taken from a Citronelle sandstone and treated to change their wettability characteristics. The results obtained for four

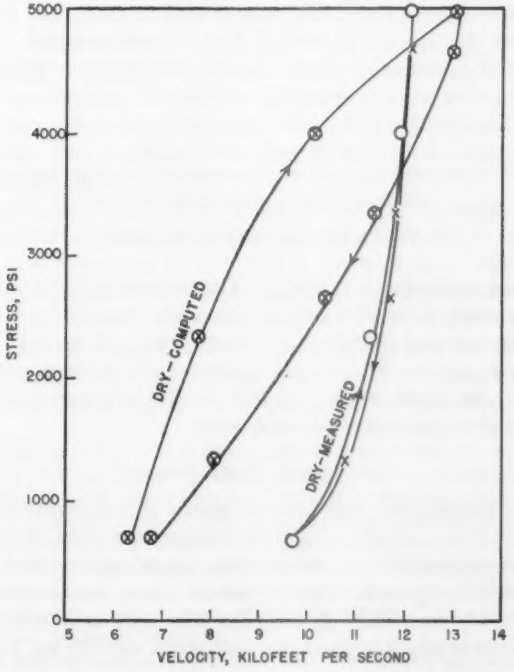


FIG. 22. Measured velocities and velocities computed from equation (2).

of these samples are plotted in Figure 23. It may be noted that they fall in two groups.

The dry cores and the preferentially oil-wet, water-saturated cores lie in the first group and give about the same measured velocity. Thus the high reflection coefficient due to the poor wetting characteristics of water is sufficient to make the first detectable arrival that which travels entirely in the rock matrix.

The remaining cases form the second group. The preferentially water-wet, water-saturated cores give velocities close to the time-average line, as is also

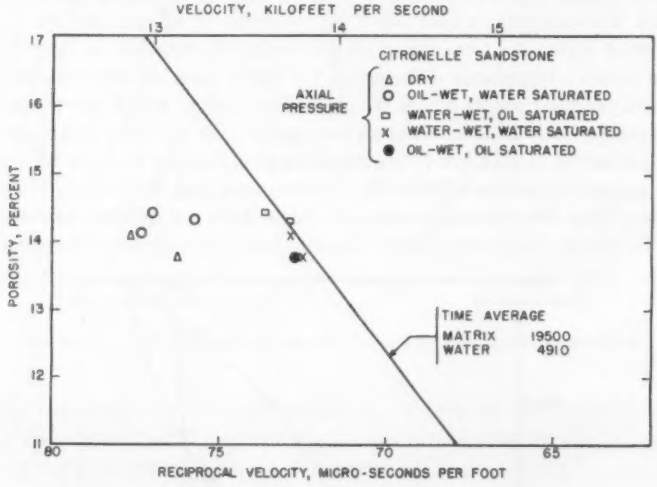


FIG. 23. Effect of wettability on velocity.

shown for Berea sandstone in Figure 11. The preferentially water-wet (i.e., very clean), oil-saturated cores give almost the same velocity because the oil fills the pendular spaces, and the signal path lies in the rock matrix except where it crosses pendular spaces. Finally, the preferentially oil-wet and oil-saturated core gives again the same velocity because the oil easily wets the surface and no gas remains to give high reflection coefficients.

PRACTICAL IMPLICATIONS

Our studies to date have been devoted largely to investigations in the laboratory. As yet we have not been able to make extensive tests of the applicability to field problems of conclusions drawn from the laboratory work. Nevertheless certain conclusions of practical import can be drawn rather easily. We present some of these here tentatively in the hope that they may serve as a guide to others. Our ultimate aim is to make the continuous velocity log, now coming into

wide use as a routine log, of greater quantitative use to the geologist and petroleum engineer as well as the geophysicist.

The problem of porosity determination from velocity data seems to divide itself into three parts. These are (a) consolidated rocks with homogeneous porosity, e.g., consolidated sandstones and oolitic limestones, (b) unconsolidated sands, and (c) rocks with heterogeneous porosity, e.g., vugular and fractured carbonate rocks.

Under (a) we suggest that a simple time-average formula be used with a rock matrix velocity of about 19,500 ft/sec for sandstones[1] and 22,500 ft/sec for limestones.[2] A fluid velocity of about 5,000 ft/sec seems appropriate. In special cases a velocity based on the temperature, salinity, and pressure of the mud filtrate may be more suitable. Data to estimate the effects of these three variables on velocity have been conveniently summarized by Wyllie (1957). Uncertainties in the use of the time-average formula include the best solid velocities to choose and the possibility that at shallow depths, and particularly in the case of lightly cemented rocks, the effective overburden pressure will be insufficient to lead to the attainment of a terminal velocity capable of being closely approximated by the simple time-average formula. Only an intensive inspection of reliable continuous velocity logs and core data can resolve these uncertainties.

Under (b) it can only be said that, if genuine first arrivals are measured by continuous velocity logs, the velocities are likely to be less than those predicted by a time-average equation. In the light of present data on unconsolidated sands, limited in scope as they admittedly are, we would still suggest using a time-average equation. The possibility that porosities then deduced are somewhat too large should not be overlooked.

In carbonate rocks with purely vugular porosity it seems probable that porosities estimated from velocities by means of a time-average equation will be too small. If this proves to be the case a comparison of velocity-estimated porosities with porosities deduced from neutron logs or gamma-gamma density logs should lead directly to the estimation of the extent of the vugular porosity. If vugular porosity is a large fraction of the total porosity the existence of permeability undetectable by contact logging would be a reasonable inference. In wildcat wells where zones suitable for testing are few and where the existence

[1] Matrix velocities as used in the time-average relationship are based on the velocities of pure crystals. In crystals there is pronounced velocity anisotropy which is dependent on the axis along which measurements are made. The velocity of quartz crystals varies from about 17,500 to 21,500 ft/sec. Occasionally sandstones are found which appear to have matrix velocities as low as 17,500 ft/sec or as high as 21,500 ft/sec. It is possible that such sandstones contain sand grains which are preferentially orientated along some particular crystal axis. The majority of sandstones, however, are believed to have essentially random orientation of grains. A random orientation of sand grains would tend to give an average matrix velocity of about 19,500 ft/sec. This average matrix velocity is the one most frequently observed in practice.

[2] This figure is based on measurements we have made of the velocity for calcite crystals.

of permeability is the essential criterion for perforating, such a diagnosis would be most valuable. In fractured rocks or vugular and fractured rocks two possibilities exist. The first is that just discussed; the second is that the cracks, particularly if gas is present, may lead to a signal attenuation which is so large that the recorded signal may not be that of the true first arrival, i.e., the velocity recorded will be anomalously low.[3] Interpretation of such arrivals by the time-average formula would lead to apparent porosities much greater than those based on nuclear log data. Again the existence of permeability could be reasonably deduced from a comparison of the apparent porosities derived from the velocity and nuclear logs.

The direct location of zones of hydrocarbon saturation using a continuous velocity log has been discussed by Hicks and Berry (1956). These authors presented field data which seem to indicate that porous zones containing oil or gas may have velocities significantly lower than otherwise similar zones containing water only. We have observed similar differences between the velocities in certain sands containing gas above and below a gas-water contact. The observation has not been uniform, i.e., in some sands we have seen large differences, in others none. In at least one instance, the apparent velocity in the gas sand was far less than any velocity we have measured in the laboratory; indeed it approximated that of a rich brine. We suggest that these lowered velocities are not true first arrivals of the imposed energy but rather arrivals taking minimum time with energy sufficient to actuate the recording equipment. Experiments in which logs are run with different input energies or detector sensitivities should serve to resolve this question. Should it transpire that certain types of sands and particularly ones containing hydrocarbons lead to a rapid deterioration in signal strength and anomalously low apparent velocities, a valuable diagnostic method would become available. Log interpretation is in essence the art of detecting anomalies.

Our data on consolidated rocks under pressure indicate rather decisively that if first arrivals are recorded the rock velocity will not be significantly affected by the presence within the pores of gas and oil in addition to water, unless gas is the phase wetting the rock. This is improbable. Far from being a drawback to the use of continuous velocity logs in log interpretation, such a conclusion, if practically substantiated, is of great value. If a formation, for example, is of constant velocity and inconstant resistivity it probably contains hydrocarbons. Similarly if the velocity-derived porosity of a rock is much larger than the porosity deduced electrically, hydrocarbon saturation is again to be inferred. Relationships between velocity, resistivity, S.P., and saturation can easily be drawn up for rocks free of an appreciable shale content. For dirty sands, however, the problem is somewhat more complex.

When logging in oil-base muds in which contact logging devices are useless,

[3] M. P. Tixier has indicated to one of us (Wyllie) that he has already observed this effect.

the continuous velocity log provides a means for estimating porosity and, hence, formation factor and R_{z0}.

CONCLUSIONS

From the laboratory data so far obtained we may draw the following tentative conclusions.

(1) To obtain simple and meaningful data from natural consolidated rocks it is necessary to apply a large differential pressure so that a terminal velocity is approached. Under these circumstances the rock material may be considered perfectly homogeneous; at low pressures the flaws and cracks in the matrix lower the measured velocity appreciably.

(2) For consolidated rock saturated with a high-velocity fluid, at high differential pressure, the time-average formula is a good approximation. If the saturant has a low velocity, the measured velocity is independent of the nature of the fluid.

(3) Signal attenuation in an unconsolidated medium is a major factor and merits more study. It seems possible that it may provide a useful diagnostic tool for well logging.

(4) The concept that the first arrival travels along certain paths, which minimize the transit time, can be extended in a reasonable way to account for the effects of wettability.

(5) By supplementing other logs the continuous velocity logger may yield important information on intercrystalline porosity, vugular porosity, fractures, and permeability which is not otherwise obtainable.

REFERENCES

Bobek, J. E., Mattax, C. C., and Denekas, M. O., 1957, Reservoir rock wettability—its significance and evaluation: A.I.M.E. Preprint.

Hicks, W. G., and Berry, J. E., 1956, Application of continuous velocity logs to determination of fluid saturation of reservoir rocks: Geophysics, v. 21, p. 739–754.

Hughes, D. S., and Kelly, J. L., 1952, Variation of elastic wave velocity with saturation in sandstone: Geophysics, v. 17, p. 739–752.

Iida, K., 1939, Velocity of elastic waves in a granular substance: Bulletin of the Earthquake Research Institute, v. 17, p. 783–807.

Love, A. E. H., 1944, A treatise on the mathematical theory of elasticity, 4th ed.: New York, Dover Publications, p. 296.

Wood, A. B., 1941, A textbook of sound: New York, The Macmillan Company.

Wyllie, M. R. J., 1957, The fundamentals of electric log interpretation, 2nd ed.: New York, Academic Press.

———, Gregory, A. R., and Gardner, L. W., 1956, Elastic wave velocities in heterogeneous and porous media: Geophysics, v. 21, p. 41–70.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 494–505, 6 FIGS.

SOUND VELOCITY vs. TEMPERATURE IN WATER-SATURATED SEDIMENTS*

GEORGE SHUMWAY†

ABSTRACT

Sound velocity vs. temperature was measured in a continental shelf silt, a calcareous ooze, a deep-sea red clay, a continental slope clay, and a quartz sand using a resonant chamber technique. The temperature effect on these water-saturated sediments was approximately the same as for water alone; this similarity to water behavior would be expected inasmuch as the compressibility of a water-sediment mixture is dominantly due to the relatively large water compressibility.

INTRODUCTION

Compressional velocity has been measured as a function of temperature in 5 distinctive sediments, i.e., a continental shelf silt, a calcareous ooze, a deep-sea red clay, a continental slope clay, and a quartz sand. Such information is needed if one is to use laboratory measurements of velocity made at room temperature as a guide to the velocities *in situ;* also it can be an aid to understanding the complexities of acoustic propagation in mixtures of solid particles and fluid.

A number of laboratory studies of sound velocity in consolidated sedimentary rocks are reported in the literature, and in a few cases the effects of temperature have been reported (Hughes and Cross, 1951; Hughes and Kelly, 1952). Almost no temperature-velocity data have been reported for unconsolidated water-saturated sediments. Sutton et al. (1957) made a few velocity measurements at different temperatures on two samples and noted the dominant role played by water compressibility and the large effect of temperature on compressibility.

SIMPLE THEORY

The compressional velocity in a composite mixture of fluid and solid particles can be predicted, approximately, by considering that the various components contribute to the bulk density and compressibility of the mixture in proportion to their fractional part of the total volume. When rigidities are negligible, as in high-porosity fine-grained sediments, this relation (Wood, 1941; Urick, 1947) may be expressed as follows for sediments:

$$C_{ws} = \sqrt{\frac{1}{(\sum f_{si}\rho_{si} + f_w\rho_w)(\sum f_{si}\beta_{si} + f_w\beta_w)}} \qquad (1)$$

where

C_{ws} is sound velocity in the water-sediment mixture

f_{si} are volume fractions of sediment particles of the i mineral types

* Manuscript received by Editor November 18, 1957.

† United States Navy Electronics Laboratory, San Diego 52, California.

f_w is volume fraction of water
β_{si} are sediment particle compressibilities for the i minerals
β_w is water compressibility
ρ_{si} are sediment particle densities for the i minerals
ρ_w is water density.

If rigidity is not negligible, the equation becomes

$$C_{ws} = \sqrt{\frac{K_{ws} + 4/3\mu}{\sum f_{si}\rho_{si} + f_w\rho_w}} \tag{2}$$

where μ is the rigidity modulus of the sediment and

$$K_{ws} = \frac{1}{\sum f_{si}\beta_{si} + f_w\beta_w}.$$

Some values of compressibilities are as follows:

Compressibility, cm²/dyne	Material	Temperature, °C	Source
50.92×10^{-12}	Distilled water	0	Beyer (1954)
46.39×10^{-12}	Sea water, 34.7 parts per thousand	0	Computed from sound velocity (Del Grosso (1952))
2.697×10^{-12}	Quartz	20	Birch et al. (1942)
1.35×10^{-12}	Calcite	0	Birch et al. (1942)
1.0×10^{-12}	Kaolin	Room	Urick (1947)

The relatively large water compressibility dominates the compressibility factor when numerical values are used in equations (1) and (2). The temperature effect on water compressibility is considerable, whereas it is small for quartz and calcite; as temperature drops from 50°C to 0°C, water compressibility increases by 20.5 percent, but quartz and calcite compressibilities decrease by about 2.2 percent. These relationships have been plotted (Figure 1), the data being obtained as follows: pure water from Randall (1932), sea water computed from sound velocity (Del Grosso, 1952) and density (La Fond, 1951), quartz and calcite from Birch et al. (1942).

Distilled-water density changes about 4 percent between 0°C and 100°C (Lindsay, 1957, p. 2–138); for sea water of 35 parts per thousand salinity, density changes about 6 percent between 0°C and 100°C (LaFond, 1951). Quartz density changes by 0.36 percent between 20°C and 100°C, while calcite density changes by 0.08 percent in the same temperature range (Birch et al., 1942).

EXPERIMENTAL PROCEDURE

Sound velocities were measured by a resonance method (Shumway, 1956) which utilizes a thin-walled plastic cylinder as a pressure-release container to hold sediment samples. Velocities were determined from resonant frequencies

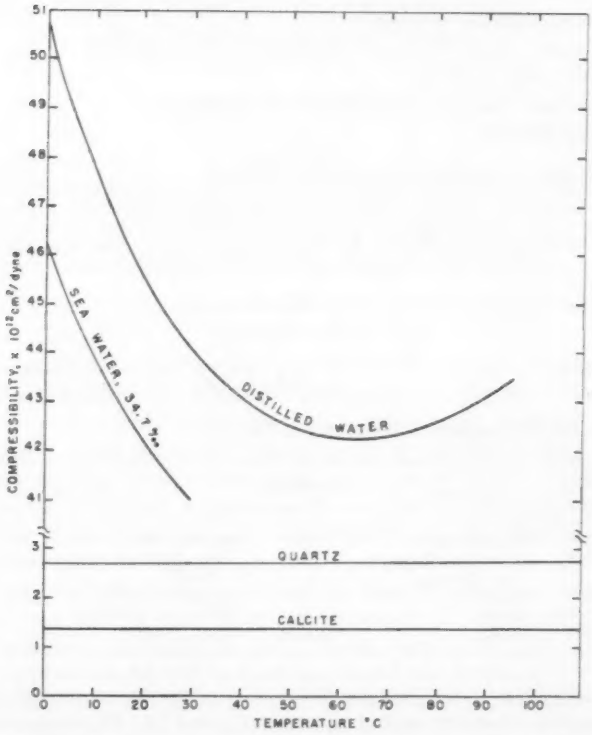


FIG. 1. Compressibility vs. temperature for pure water, sea water, quartz, and calcite.

which lay between 24 and 32 kc/sec. The absolute accuracy of the velocity measurements is considered to be ± 75 ft/sec, but the relative accuracy of successive measurements on the same sample is higher. Experimental values for distilled water (Figures 2, 3, 4, 5, 6) do not deviate from a smooth curve by more than 5 ft/sec, with the exception of a few values. For sediments these deviations are higher, but they are less than ± 25 ft/sec in most cases.

Temperatures were measured by a mercury-in-glass thermometer with a bulb only $\frac{1}{8}$ inch in diameter which was inserted into the center of the sediment for each reading. The temperature was measured immediately after each velocity measurement.

Resonating air bubbles within a sediment can interfere greatly with the operation of the resonant chamber. A water sample or water-saturated sediment in equilibrium with the atmosphere may develop visible bubbles when heated 15°C to 20°C. To minimize bubble difficulties, velocity measurements usually were started at the highest practical temperature and were continued as the

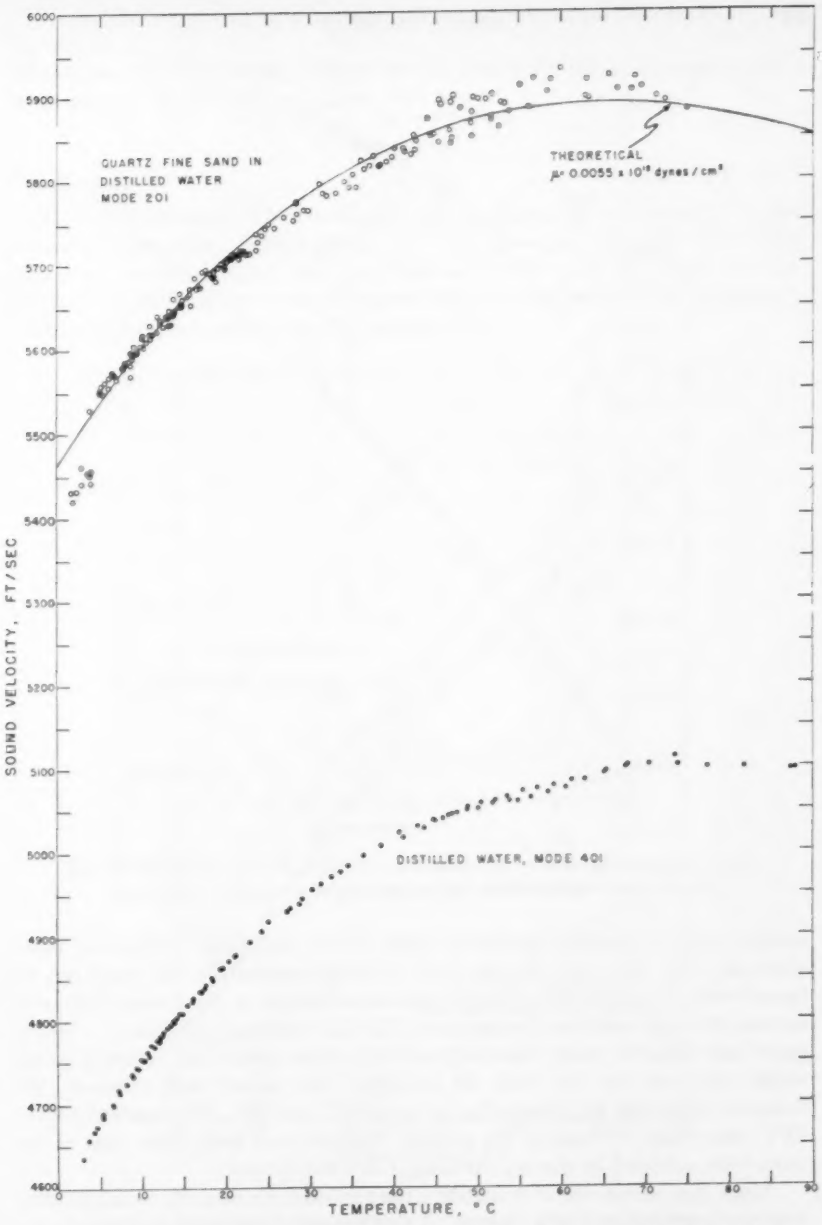


FIG. 2. Compressional velocity measurements vs. temperature in water-saturated quartz fine sand, compared with theory. Distilled-water measurements are given for comparison.

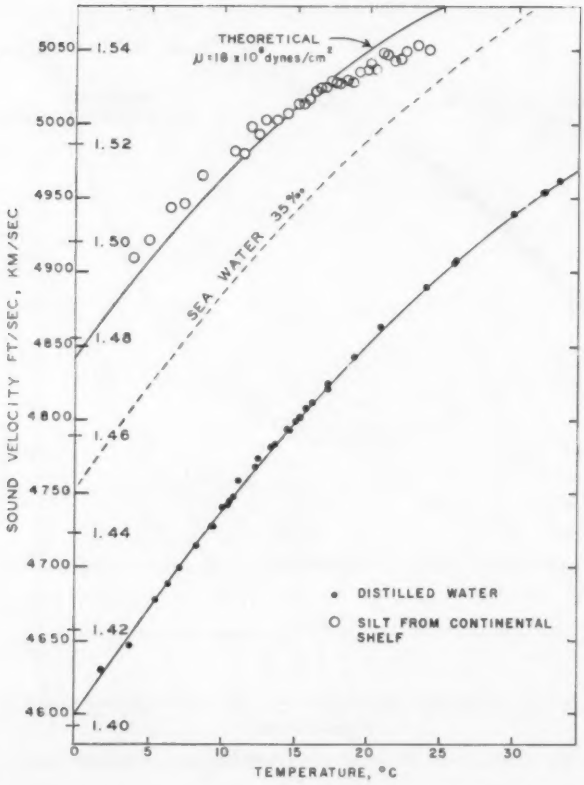


FIG. 3. Compressional velocity measurements vs. temperature in a continental shelf silt. Distilled-water measurements, and sea-water curve are given for comparison.

temperature was lowered gradually. Four of the sediments (calcareous ooze, slope clay, red clay, silt) initially were at room temperature and could not be heated without bubbles being formed, so measurements on these were made only between freezing and room temperature. The fifth sediment, a mixture of quartz grains and distilled water, was prepared with warm grains and boiling distilled water. However, by the time the container was packed with sediment the temperature always had dropped to between 50°C and 60°C. Measurements up to 75°C were made by heating the sample. Temperatures lower than that of the room were achieved by placing the sample in a refrigerator.

More than one series of descending temperatures-vs.-velocity measurements were made for each sediment sample. A single series of measurements usually in-

volved most of a day's time, hence for each sediment the measurements were made on at least two different days.

SEDIMENTS

Quartz sand

A piece of friable St. Peter sandstone was disaggregated mechanically to give a natural quartz sand of high purity. This was sieved so that only grains with diameters between $\frac{1}{4}$ and $\frac{1}{8}$ mm (i.e., fine sand) were used. The sediment wet density was 2.07 gm/cm³ when saturated with distilled water, and its porosity (volumetric water content) was 36.3 percent.

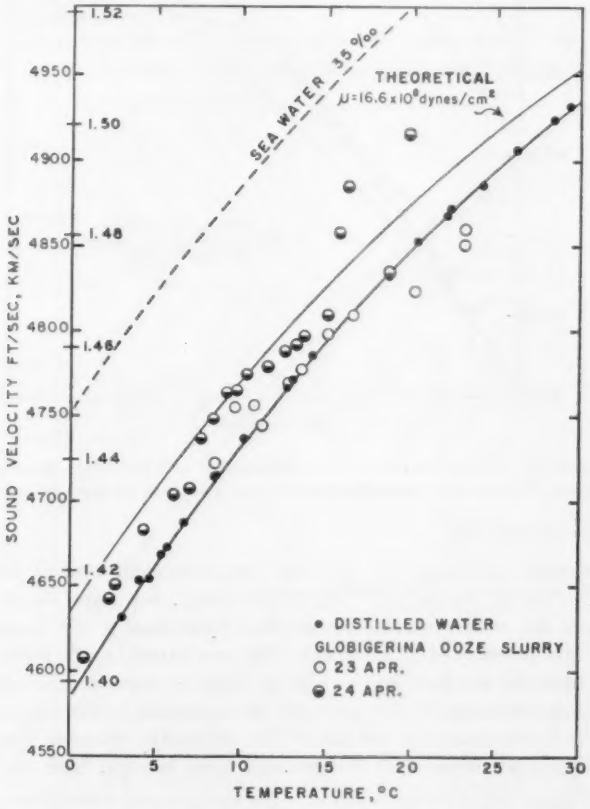


FIG. 4. Compressional velocity measurements vs. temperature in a Globigerina ooze slurry. Distilled-water measurements and sea-water curve are given for comparison.

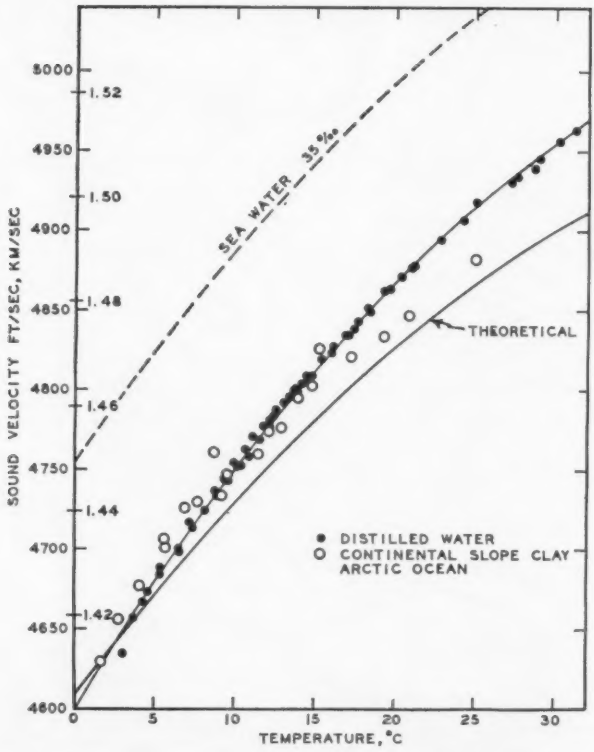


FIG. 5. Compressional velocity measurements vs. temperature in a continental slope clay from the Arctic Ocean. Distilled-water measurements and sea-water curve are given for comparison.

Silt from continental shelf

This sediment was taken by core from the outer shelf west of Point Loma, California, 32°41′27″ N. Lat., 117°18′30″ W. Long., in a water depth of 45 fm. It was coarse silt with a median diameter of 0.046 mm, a wet density of 1.79 gm/cm³, and a porosity of 62.3 percent. The core barrel in which this sediment was taken from the sea floor was smaller in diameter than the container for the resonance measurements, so the sediment was disturbed to the extent necessary to pack it into the resonance container. The interstitial water in this sediment was the original sea water that it contained when brought from the sea floor.

Calcareous ooze

This sediment was dredged from the top of Cape Johnson Guyot in the Central Pacific in 1950 (Hamilton, 1956), where the water depth was about

1,000 fm. It is almost pure calcium carbonate, and it is a modern Globigerina ooze composed of Foraminifera tests and finely divided material. In the time since 1950 the sediment had dried out. A sample for the resonance measurements was prepared by soaking the material in a large volume of distilled water for many weeks. This essentially eliminated the natural sea salts left behind in the sediment when the original water evaporated. The prepared sediment had a wet density of 1.57 gm/cm^3 and a porosity of 66.6 percent. The median diameter was 0.037 mm (coarse silt). The solid material was composed of 27 percent sand-sized particles, 54 percent silt-sized particles, and 19 percent clay-sized particles by weight, using the Wentworth classification.

Continental slope clay

This sediment was taken by core in the Arctic Ocean from a water depth of 2,203 m, on U.S.S. "Staten Island," 1 September 1957, at 71°29′ N. Lat., 149°34′

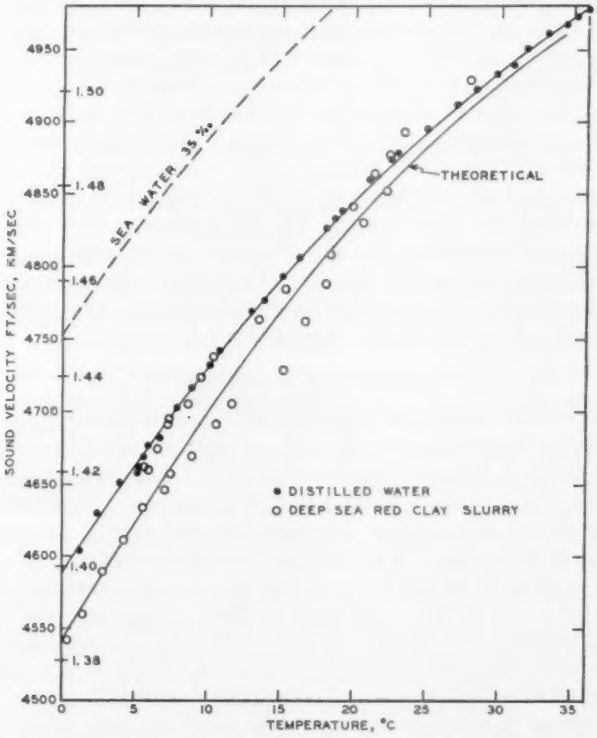


FIG. 6. Compressional velocity measurements vs. temperature in a deep-sea red-clay slurry. Distilled-water measurements and sea-water curve are given for comparison.

W. Long. The original core was $1\frac{3}{8}$ inches in diameter and 34 inches long. The lower $14\frac{3}{8}$ inches of the core was used for the resonant chamber sample. The sediment originally had a wet density of 1.34 gm/cm³. The resonant chamber was two inches in diameter, so deformation of the original material was unavoidable in packing the resonant chamber. The sediment density in the resonant container was 1.31 gm/cm³, and the porosity was 82.6 percent. The median diameter of the particles was 0.0025 mm (coarse clay). The particles consisted of 63 percent clay, 36 percent silt, and one percent sand by weight.

Deep-sea red clay

This sediment was taken by core in the North Pacific Ocean, from a water depth of 5,220 m, on R/V "Spencer F. Baird" of the Scripps Institution of Oceanography, 9 August 1954, at 37°15′ N. Lat., 143°07′ W. Long. It is a red clay containing very few Foraminifera tests or other coarse material. X-ray diffractometer runs before and after roasting at 600°C for 4 hours indicated the presence of kaolinite. Another core taken at the same station was found by R. W. Rex (personal communication) to contain 14.5 percent quartz. The sediment had dried out considerably, so it was necessary to saturate the sample with distilled water to bring it back to the soft condition which exists at the upper surface of fresh red-clay sediments as they lie on the sea floor. A slurry was made of the sediment, and this was passed through a sieve with openings of 0.0625 mm to remove lumps and the few coarse grains which were in the original sediment. The median diameter of the particles was 0.0015 mm (medium clay). The particles consisted of 80 percent clay and 20 percent very fine silt, by weight. The wet sediment porosity was 80.9 percent. This is within the range of natural red clays, so the salinity of the interstitial water probably was close to that originally in the sediment. The sediment wet density was 1.34 gm/cm³.

EXPERIMENTAL RESULTS

For purposes of comparison, sound velocity in distilled water was measured as a function of temperature by the same resonance method used for the sediments (Figures 2, 3, 4, 5, 6). These distilled water values (mode 401) agree with Del Grosso's (1952) values to within a few feet per second. Also included on some of the velocity-vs.-temperature diagrams, for comparative purposes, is Del Grosso's curve for sea water of 35 parts per thousand salinity.

Quartz sand—One hundred and ninety-one measurements, using resonant mode 201 (25.3–27.6 kc/sec), were made in the temperature range 1.6°C–75°C (Figure 2). Velocities were about 17 percent higher than for distilled water. They show a rise with temperature similar to water alone. Maximum velocities of about 5,900 ft/sec (1.8 km/sec) were found between 60°C and 70°C.

A theoretical velocity-temperature curve was computed, using the known porosity together with appropriate quartz and water densities and compressibil-

ities in equation (2), which fits the experimental data reasonably well. Rigidity is appreciable in this sediment; velocities computed using equation (1) (no rigidity) lie about 340 ft/sec lower than the measured values. Hamilton et al. (1956) found rigidities for natural fine sand and very fine sand by using measured velocities and densities in an expression equivalent to equation (2) of this paper. The mean rigidity for 6 very fine sands was 52×10^8 dynes/cm^2, and for 17 fine sands it was 56×10^8 dynes/cm^2. For the present study (Figure 2) a rigidity of 55×10^8 dynes/cm^2 was assumed, which caused the theoretical curve to fall close to the measured values. It was assumed that this rigidity did not change with temperature.

Continental shelf silt—Thirty-four measurements were made, using resonant mode 401 (30.6–31.4 kc/sec), in the temperature range 4°C–24°C (Figure 3). Sound velocities were approximately 4.6 percent greater than distilled water velocities; the rate of increase of velocity with temperature was slightly less than for water.

A theoretical velocity curve was computed assuming that all of the particles were quartz. Silt sediments from the region where this sample was taken generally contain about 5 percent heavy minerals (Emery et al., 1952). This sediment, being more porous than the quartz sand, had a lower rigidity. A rigidity of 18×10^8 dynes/cm^2 was found to cause the theoretical curve to fall within the experimental values. The theoretical curve is slightly steeper than the trend of the experimental values.

Calcareous ooze—Thirty-one measurements were made, using resonant mode 401 (28.7–30.6 kc/s), in the temperature range 0.8°C–23°C (Figure 4). Sound velocities were close to distilled-water values, being about 0.5 percent greater. The trend of the experimental values closely parallels the distilled-water curve.

A theoretical velocity curve was computed, assuming that all of the particles were calcite. This sediment was more porous than the continental shelf silt, hence a smaller rigidity was called for. A rigidity of 16.6×10^8 dynes/cm^2 caused the theoretical curve to fall within the experimental values. This theoretical curve is slightly less steep than the distilled-water curve.

Continental slope clay—Twenty measurements were made, using resonant mode 401 (30.3–28.8 kc/sec), in the temperature range 0.64°C–25°C (Figure 5). The velocity values closely parallel distilled water and lie almost on top of them, but at the higher temperature end the values fall slightly below the water curve, suggesting a velocity increase with temperature that is slightly less steep.

A theoretical velocity curve was computed, assuming that all of the particles were quartz. For this high-porosity sediment the rigidity was neglected, and equation (1) was used. The theoretical curve is only slightly lower than the experimental points. It is less steep than the distilled-water curve, a fact which is in agreement with the trend suggested by the experimental values.

Deep-sea red clay—Thirty-three measurements were made, using resonant mode 401 (28.2–30.1 kc/sec), in the temperature range 0.39°C–29.8°C (Figure 6).

The velocity values parallel the distilled-water curve rather well and in general lie slightly below it. The trend of the sediment velocity values may possibly be steeper than the distilled-water curve.

To compute a theoretical velocity curve for this sediment one must know the mineralogical composition of the clay and the compressibilities of the clay minerals as a function of temperature. A modal analysis technique is available for fine-grained mixtures (Schmalz, 1957), but the compressibility data probably do not exist. Nevertheless, by assuming the sediment to consist of a mixture of 15 percent quartz and 85 percent "clay" by volume, and by assuming a suitable change of "clay" compressibility with temperature, a theoretical velocity curve was computed which fit the experimental points rather well (Figure 6). The necessary "clay" compressibility values for this curve ranged from about 9×10^{-12} cm^2/dyne at 0°C to 0.75×10^{-12} cm^2/dyne at 30°C.

In conclusion, this study has shown that sound velocity changes with temperature in five distinctive water-saturated sediments at about the same rate as for water alone. This is attributed to the dominant role played by water compressibility in determining the bulk compressibility of the sediment, and the relatively large temperature effect on the water compressibility.

ACKNOWLEDGMENT

John Newton and Kim Igleman performed the sediment analyses. Drs. E. L. Hamilton, G. H. Curl of the Navy Electronics Laboratory, and R. W. Raitt and L. N. Liebermann of the Scripps Institution of Oceanography have critically read the manuscript and made suggestions for its improvement.

REFERENCES

Beyer, R. T., 1954, Formulas for sound velocity in sea water: Sears Found. Jour. Mar. Res., v. 13, p. 113–121.

Birch, F., Schairer, J. F., and Spicer, H. C., 1942, Handbook of physical constants: GSA, Special Paper 36.

Del Grosso, V. A., 1952, The velocity of sound in sea water at zero depth: U.S.N.R.L. Report 4002.

Emery, K. O., Butcher, W. S., Gould, H. R., and Shepard, F. P., 1952, Submarine geology off San Diego, California: Jour. Geology, v. 60, p. 511–548.

Hamilton, E. L., 1956, Sunken islands of the Mid Pacific mountains: GSA, Memoir 64.

———, Shumway, G., Menard, H. W., and Shipek, C. J., 1956, Acoustic and other physical properties of shallow-water sediments off San Diego: Jour. Acoust. Soc. Am., v. 28, p. 1–15.

Hughes, D. S., and Cross, J. H., 1951, Elastic wave velocities at high pressures and temperatures: Geophysics, v. 16, p. 577–593.

Hughes, D. S., and Kelly, J. L., 1952, Variation of elastic wave velocity with saturation in sandstone: Geophysics, v. 17, p. 739–752.

LaFond, E. C., 1951, Processing oceanographic data, U. S. Navy Hydro. Office Pub. No. 614.

Lindsay, R., 1957, Density and compressibility of liquids: Amer. Inst. Physics Handbook, section 2, p. 136–164.

Randall, C. R., 1932, Ultrasonic measurements of the compressibility of solutions and of solid particles in suspension: Bur. Standards Jour. Research, v. 8, p. 79–99 (R.P. 402).

Schmalz, R. F., 1957, Quantitative X-ray modal analysis of sediments from the Peru-Chile trench: Bull. GSA, v. 68, p. 1793.

Shumway, G., 1956, A resonant chamber method for sound velocity and attenuation measurements in sediments: Geophysics, v. 21, p. 305–319.

Sutton, G. H., Berckhemer, Hans, and Nafe, J. E., 1957, Physical analysis of deep sea sediments: Geophysics, v. 22, p. 779–812.

Urick, R. J., 1947, A sound velocity method for determining the compressibility of finely divided substances: Jour. Appl. Physics, v. 18, p. 983–987.

Wood, A. B., 1941, A textbook of sound: London, G. Bell and Sons.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 506–519, 14 FIGS.

MAXIMUM GRAVITY EFFECT OF CERTAIN SOLIDS OF REVOLUTION*

LESLIE DUSKA†

ABSTRACT

This paper presents formulae for calculating the gravitational attraction, at points on their central vertical axes, of several solids of revolution. Such calculations are sometimes desirable to find the maximum anomalies which may be caused by geologic bodies which are assumed to have the approximate shape of a solid of revolution. A reasonable set of density differences must be used in such preliminary gravity calculations to find the limits of the anomalies to be expected. A table of formulae is presented.

INTRODUCTION

The attraction force of a solid of revolution on a unit particle P in its axis can be calculated by a triple-integration throughout the whole body

$$F_w = k \cdot \delta \iiint_V \frac{dV}{r_w^2}, \tag{1}$$

where F_w (of magnitude F) and r_w are vectors, r_w being the variable distance from P to the points of the body.

Supposing the body is homogeneous, the resultant attraction will be along the axis, and it is necessary to compute only this component. Two of the three integrations can be eliminated by using the attraction formula of a circular lamina (see Figure 1a):

$$F = 2\pi \cdot k \cdot \delta \left(1 - \frac{d}{r}\right), \tag{2}$$

or

$$F = 2\pi \cdot k \cdot \delta (1 - \cos \alpha). \tag{3}$$

The third integration will be performed by expressing

$$\cos \alpha = \frac{d}{r}$$

after the characteristic of the generating shape. Thus the attraction of the entire body is as shown in Figure 1b:

$$F = 2\pi \cdot k \cdot \delta \int_{x_1}^{x_2} (1 - \cos \alpha) dx \tag{4}$$

* Manuscript received by the Editor May 1, 1956.
† Exploration Consultants, Inc., Calgary, Alberta, Canada.

where

$\cos \alpha = x/\sqrt{x^2+\rho^2}$

x = distance of lamina from P

ρ = radius of lamina

k = Newtonian constant

δ = density (or density contrast).

The fundamental equation (4) is used to develop the force of attraction of the several solids of revolution shown below.

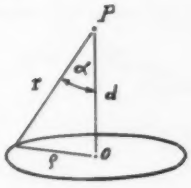
Attraction force of a few solids of revolution

The attraction force of a few solids of revolution will be demonstrated on their respective figures, including the extreme cases.

Figures 2a and 2b show the attraction of a right circular cone.

Figure 3: Frustum of a right circular cone.

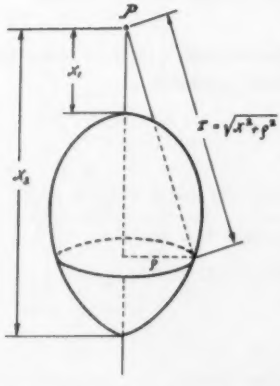
As the cylinder is a frustum with the apex of its complement at infinity, the



$$F = 2\pi \cdot k \cdot \delta \left(1 - \frac{d}{r}\right) \qquad (2)$$

$$\text{or} \quad F = 2\pi \cdot k \cdot \delta \left(1 - \cos \alpha\right) \qquad (3)$$

FIG. 1a. Attraction force of a circular lamina for a unit particle P above its centerpoint.



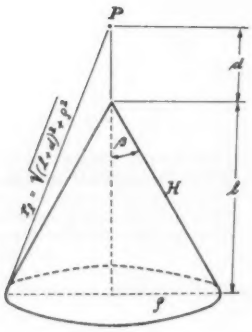
$$F = 2\pi \cdot k \cdot \delta \cdot \int_{x_1}^{x_2} (1 - \cos\alpha)\, dx \qquad (4)$$

where $\cos\alpha = \dfrac{x}{\sqrt{x^2+\rho^2}}$

x = distance of lamina from P

$\rho = f(x)$

FIG. 1b. Attraction force of any solid of revolution on a unit particle P in its axis.



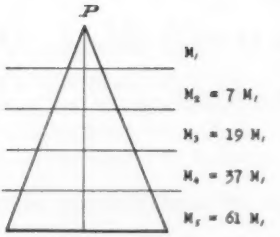
$$F = 2\pi \cdot K \cdot \delta \int_{r_1 = d}^{r_2 = d+l} \left(1 - \frac{x}{\sqrt{x^2 + \left[\rho/_R (x-d)\right]^2}}\right) dx$$

$$F = 2\pi \cdot K \cdot \delta \left[l - (r_2 - d)\cos^2\beta - d\cos\beta \cdot \sin^2\beta \cdot \ln\left\{\frac{r_2 + H + d\cos\beta}{d + d\cos\beta}\right\}\right] \quad (5)$$

For a unit particle P on the apex, d = 0, $r_2 = H$,

$$F = 2\pi \cdot K \cdot \delta \cdot l\,(1 - \cos\beta) = (\text{Bouguer's corr.}) \times (1 - \cos\beta) \quad (6)$$

FIG. 2a. Attraction of a right circular cone.



$$M_n = [n^3 - (n-1)^3]M_1$$

$$F_1 = F_2 = F_3 = \ldots = F_n$$

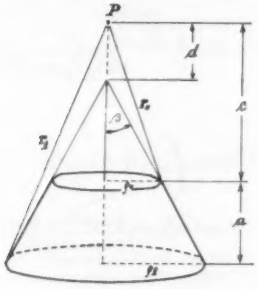
FIG. 2b. The attraction forces due to each part of a right circular cone, cut with parallel planes at equal distances and perpendicular to the axis, are equal for P on the apex.

attraction of a cylinder can be regarded as a special case, a limit of the attraction formula of a frustum which in turn is the general formula:

$$F_{\text{frustrum}} = 2\pi \cdot k \cdot \delta \left[a - (r_l - r_u)\cos^2\beta - d\cos\beta \cdot \sin^2\beta \cdot \ln\left\{\frac{r_l \cos\beta - d\sin^2\beta + (a+c)}{r_u\cos\beta - d\sin^2\beta + c}\right\}\right] \quad (7)$$

$$\lim_{\substack{d\to-\infty \\ \beta\to 0}} F_{\text{frustum}} = 2\pi \cdot k \cdot \delta[a - (r_l - r_u)] \quad (8)$$

Figure 4: Inverted right circular cone.
Figure 5: Inverted frustum of a right circular cone.
Figures 6 and 7 demonstrate a comparison between variations of attraction of



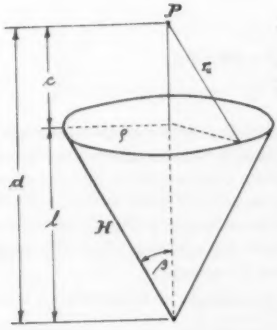
$$F = 2\pi k\delta \int_{x_1=c}^{x_2=c+a} \left(1 - \frac{x}{\sqrt{x^2+\left[\frac{\rho}{2}(x-d)\right]^2}}\right) dx$$

$$= 2\pi k\delta \left[a - (r_2 - r_1)\cos^2\beta - d\cos\beta \cdot \sin^2\beta \cdot \ln\left\{\frac{r_2\cos\beta - d\sin^2\beta + (a+c)}{r_1\cos\beta - d\sin^2\beta + c}\right\}\right] \quad (7)$$

Remarks: a) If the particle P is below the apex, the sign of d is reversed.

b) $$\lim_{\substack{d\to-\infty \\ \beta\to 0}} F_{frustum} = 2\pi k\delta \left[a - (r_2 - r_1)\right] = F_{cylinder} \quad (8)$$

FIG. 3. Attraction of a frustum of a right circular cone. As the cylinder is a frustum with the apex of its complement at infinity, the attraction of a frustum is the general formula, while that of a cylinder is a specal case.



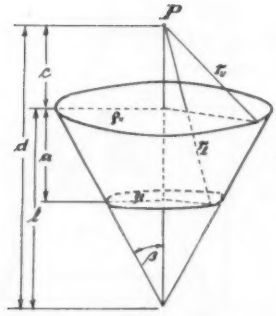
$$F = 2\pi k\delta \int_{x_1=(d-l)}^{x_2=d} \left(1 - \frac{x}{\sqrt{x^2+\left[\frac{\rho}{2}(d-x)\right]^2}}\right) dx$$

$$F = 2\pi k\delta \left[l - (d - r_1)\cos^2\beta - d\cos\beta \cdot \sin^2\beta \cdot \ln\left\{\frac{d + d\cos\beta}{r_1 - H + d\cos\beta}\right\}\right] \quad (9)$$

If P is on the centerpoint of the base, i.e. e = 0, $r_1 = \rho$, $d = l$

$$F = 2\pi k\delta \frac{l\rho}{H^2}\left[l + \rho - \frac{l\rho}{H}\ln\frac{l(H+l)}{\rho(H-\rho)}\right] \quad (9a)$$

FIG. 4. Attraction of an inverted right circular cone.



$$F = 2\pi k\cdot\delta\int_{x_1=c}^{x_2=(a+c)}\left(1-\frac{x}{\sqrt{x^2+\left[\frac{\rho}{r_2}(d-x)\right]^2}}\right)dx$$

$$F = 2\pi k\cdot\delta\cdot\left[a-(r_2-r_c)\cos^2\beta - d\cos\beta\sin^2\beta\cdot\ln\left(\frac{r_2\cos\beta-d\sin^2\beta+(a+c)}{r_c\cos\beta-d\sin^2\beta+c}\right)\right] \quad (10)$$

FIG. 5. Attraction of a frustum of an inverted right circular cone.

a right circular cone and of an inverted right circular cone from changing their altitude while keeping density and radius of bases constant.

Figure 8: Spherical segment or cap.

Figure 9: Inverted cap or lower spherical segment.

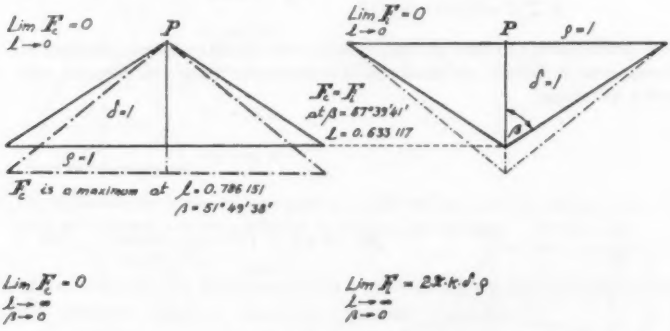


FIG. 6. A comparison between the attraction variation of a right circular cone for a particle on its apex and of an inverted right circular cone for a particle at the centerpoint of its base, as a function of their altitude, keeping density and radius of bases constant, shows that the attraction of the inverted cone varies between zero and $F_i = 2\pi k\cdot\delta\cdot\rho$ as the altitude increases from zero to infinity, while the attraction of the cone increases more rapidly (as demonstrated in Fig. 7), but after reaching a maximum it decreases and approaches zero as the altitude approaches infinity. The attraction of both cones are equal at a certain altitude l where β satisfies the equation

$$e^{\frac{1+\sin\beta-\cos\beta}{\sin^2\beta}} = \frac{\cos\beta+\cos^2\beta}{\sin\beta-\sin^2\beta} \quad (11)$$

The cone's maximum attraction occurs at the altitude

$$l = \rho\sqrt{\cos\beta}$$

where $\cos\beta = \frac{1}{2}(\sqrt{5}-1)$, $\rho = 1$, $l = 0.786151$, $\beta = 51°\,49'\,38''$.

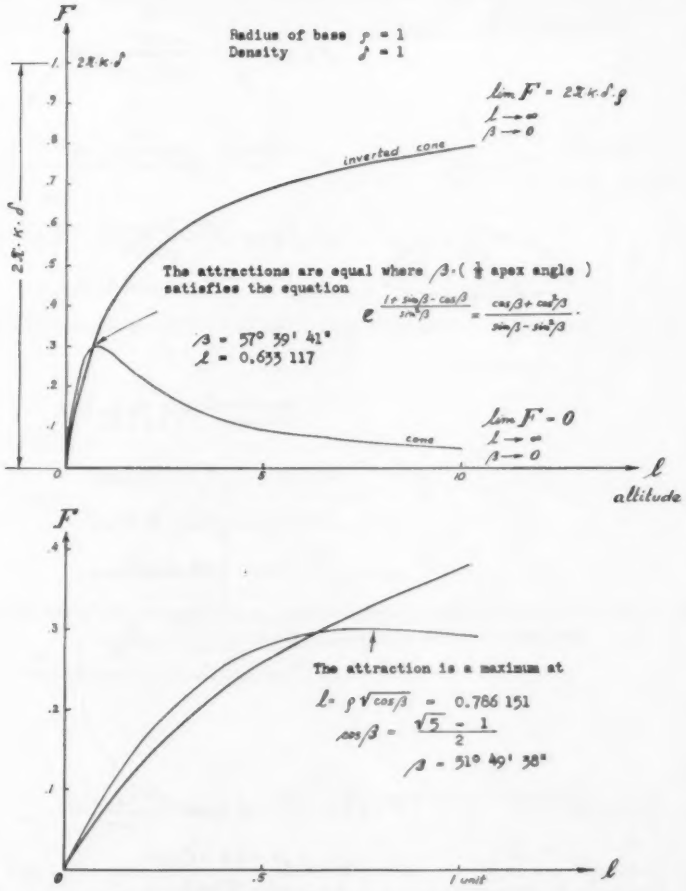


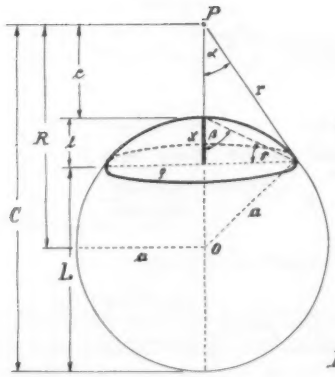
FIG. 7. Variation of attraction of a right circular cone for a particle on its apex and of an inverted right circular cone for a particle on its base as a function of their altitude.

Figure 10: Half spheres.
Figure 11: Halving the attraction of a sphere.
Figure 12: Oblate spheroid.

Variation of attraction at the pole of an oblate spheroid while it is flattened

Volume and density of the spheroid are kept constant and homogeneous (or homogeneous in confocal layers) during the process of flattening. The condition of a constant volume is given by

$$b = 1/a^2.$$



$$F = 2\pi K\delta \int_0^{\ell} \left(1 - \frac{c+x}{\sqrt{(\ell)^2 + (c+x)^2}}\right) dx$$

$$= 2\pi K\delta \int_0^{\ell} \left(1 - \frac{c+x}{\sqrt{c^2 + 2Rx}}\right) dx$$

$$F = \frac{4}{3}\pi K\delta \cdot \ell^2 \cdot \frac{(3a+c-r)}{(c+r)^2} \qquad (13)$$

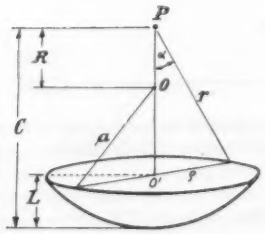
The attraction of the cap upon its vertex ($\alpha = 0$) is

$$F = 2\pi K\delta \cdot \ell \left(1 - \tfrac{2}{3}\cos\beta\right)$$

$$= 2\pi K\delta \cdot \ell \left(1 - \tfrac{2}{3}\sin\gamma\right) \qquad (14)$$

where γ = average slope.

FIG. 8. Attraction force of an upper spherical segment or cap. Equation (14) is the same as Bouguer's correction multiplied by the factor of $(1 - \frac{2}{3}\sin\gamma)$.



$$F = \frac{4}{3}\pi K\delta \frac{a^3}{R^2} - \frac{4}{3}\pi K\delta \frac{\ell^2(3a+c-r)}{(c+r)^2}$$

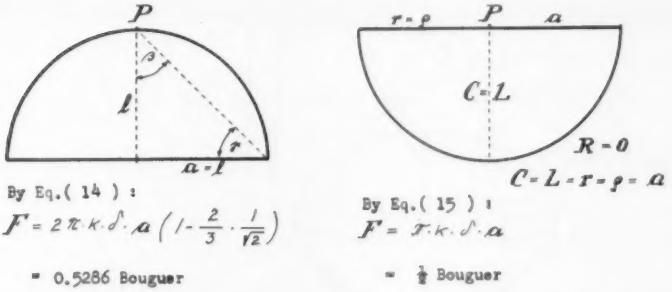
$$- \frac{4}{3}\pi K\delta \cdot L^3 \frac{(3a - C + r)}{(C+r)^2} \qquad (15)$$

Attraction of a lower segment at the centerpoint of its base ($C = L$; $r = \rho$)

$$F = \frac{2}{3}\pi K\delta \frac{(a^3 + R^3 - \rho^3)}{R^2}, \qquad (16)$$

where $R = L - a$.

FIG. 9. Attraction force of a lower spherical segment or inverted cap.



By Eq.(14) :

$$F = 2\pi \cdot K \cdot \delta \cdot a \left(1 - \frac{2}{3} \cdot \frac{1}{\sqrt{2}}\right)$$

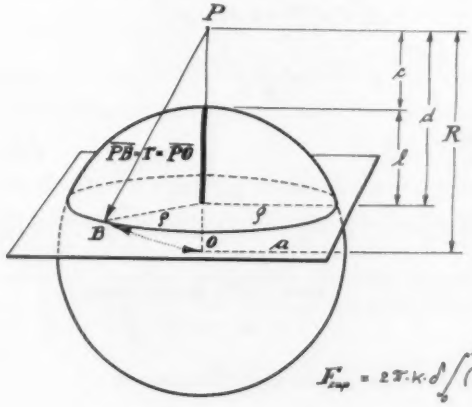
= 0.5286 Bouguer

By Eq.(15) :

$$F = \pi \cdot K \cdot \delta \cdot a$$

= $\frac{1}{2}$ Bouguer

FIG. 10. Attraction force of a half sphere on its vertex and at the centerpoint of its base.



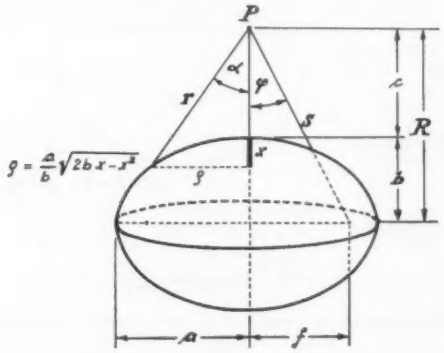
$$F_{cap} = 2\pi \cdot K \cdot \delta \int_0^l \left(1 - \frac{c+x}{\sqrt{c^2+2Rx}}\right) dx$$

$$\tfrac{1}{2} F_{sphere} = 2\pi \cdot K \cdot \delta \left[\int_0^l dx - c\int_0^l \frac{dx}{\sqrt{c^2+2Rx}} - \int_0^l \frac{x\,dx}{\sqrt{c^2+2Rx}}\right]$$

Solving for l

$$l = \frac{R^2 - c^2}{2R} \qquad r = \sqrt{\rho^2 + d^2} = R \qquad (17)$$

FIG. 11. The attraction of both parts of a bisected sphere for an outside particle P are equal if the distance r between P and the edge of the segments is equal to $R = \overline{PO}$. For a particle on the surface of the sphere the bisecting plane's vertical distance from P is $d = \frac{1}{2}a$.



$$\varrho = \frac{a}{b}\sqrt{2bx - x^2}$$

$$F = 2\pi \cdot k \cdot \delta \int_0^{2b} \left(1 - \frac{c + x}{\sqrt{-\frac{f^2}{b^4}x^4 + \left(\frac{2a^2}{b} + 2\rho\right)x + \rho^2}}\right) dx$$

$$= 4\pi \cdot k \cdot \delta \cdot \frac{a^2 b}{f^2}\left(1 - \frac{R}{f}\tan^{-1}\frac{f}{R}\right) \qquad (18a)$$

$$\text{or} \quad = \frac{3 \cdot k \cdot M}{f^2}\left(1 - \frac{R}{f}\varphi\right) \qquad (18b)$$

$$\text{or} \quad = \frac{3 \cdot k \cdot M}{f^2}\left(\frac{1}{3}t^2 - \frac{1}{5}t^4 + \frac{1}{7}t^6 - \frac{1}{9}t^8 + \cdots\right), \quad t < 1, \qquad (18c)$$

where M = Mass of spheroid

$$t = \tan\varphi = \frac{f}{R}.$$

FIG. 12. Attraction formulae of an oblate spheroid.

At the start

$$a = b = 1,$$

(Position 0 in Figure 13) i.e.,

$$F = \frac{4}{3}\pi \cdot k \cdot \delta \cdot a,$$

then F increases as a function of the major axis a,

$$F = 4\pi \cdot k \cdot \delta \frac{a^4}{(a^6 - 1)}\left(1 - \frac{\tan^{-1}\sqrt{a^6 - 1}}{\sqrt{a^6 - 1}}\right). \qquad (19)$$

The attraction will have a maximum which is defined by the first derivative (Position 1 in Figure 13)

$$\frac{dF}{da} = 0 \quad \text{or} \quad 2\phi(5x + 4) - (4x + 14)(x - 1)^{1/2} = 0 \tag{20}$$

where

$$\phi = \tan^{-1} \frac{f}{b} = \tan^{-1} \sqrt{a^6 - 1}$$

and

$$x = a^6.$$

The equation is satisfied by $a = 1.116 \ldots$ and $\phi = 44°$ approximately.

The attraction of the spheroid—with further flattening—will be equal again to that of the original sphere of equal mass, where a satisfies the equation

$$\frac{3a^4}{(a^6 - 1)}\left(1 - \frac{\tan^{-1}\sqrt{a^6 - 1}}{\sqrt{a^6 - 1}}\right) = 1. \tag{21}$$

The solution is: $a = 1.248 \ldots$ and $\phi = 59°4'$ approximately. (See Position 2 in Figure 13.)

Maximum attraction of a figure of revolution of given volume and density

It is of interest to inquire what figure of revolution gives the maximum attraction at the point where the axis pierces the surface.

The simplest consideration is that the body of uniform density must be enveloped by a surface each point of which has an equal axial component force, i.e.,

$$\frac{\cos \alpha}{r^2} \text{ must be constant and equal to } \frac{1}{l^2}.$$

Thus

$$r^2 = l^2 \cos \alpha,$$

and so

$$r = l\sqrt{\cos \alpha} \tag{22}$$

is the polar equation of the sought surface, where l is the polar axis and P is the pole (Figure 14).

The attraction force will be

$$F_{\max} = 2\pi \cdot k \cdot \delta \cdot \int_0^l \left(1 - \frac{x}{\sqrt{x^2 + \rho^2}}\right) dx$$

$$= \frac{4}{5} \pi \cdot k \cdot \delta \cdot l. \tag{23}$$

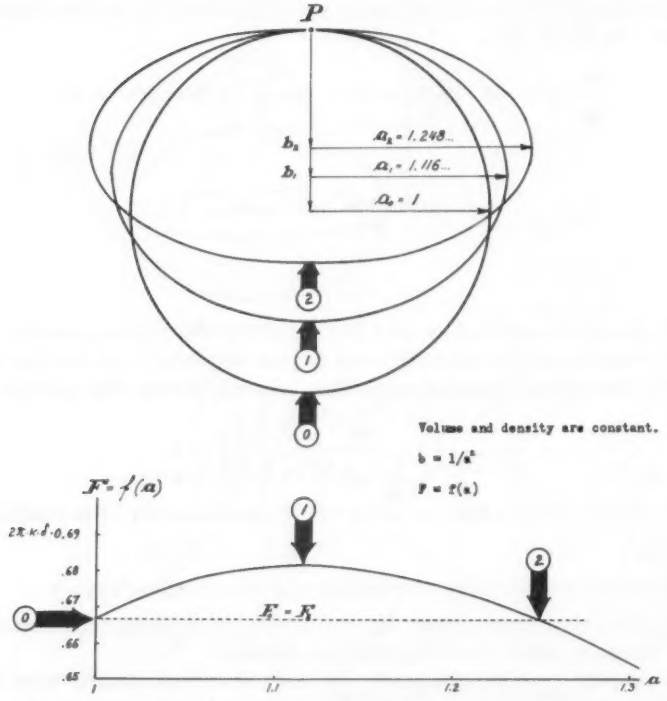


FIG. 13. Variation of attraction at the pole of an oblate spheroid while it is flattened. Volume and density are kept constant and homogeneous.

The radius a of the sphere of equal volume is given by the formula (McMillan, 1930, p. 68)

$$\pi \int_0^l \rho^2 dx = \frac{4}{3} \pi \cdot a^3$$

$$\int_0^{\pi/2} \cos^{3/2} \alpha \sin^3 \alpha d\alpha = \frac{8a^3}{9l^3}$$

$$l = \sqrt[3]{5}a. \tag{24}$$

The above maximum attraction exceeds the attraction of the sphere of equal volume and density by one part in 38 approximately:

$$\frac{F_{max}}{F_{sph}} = \frac{\frac{4}{5}\pi \cdot k \cdot \delta \cdot \sqrt[3]{5}a}{\frac{4}{3}\pi \cdot k \cdot \delta \cdot a} = \frac{3}{5}\sqrt[3]{5}.$$

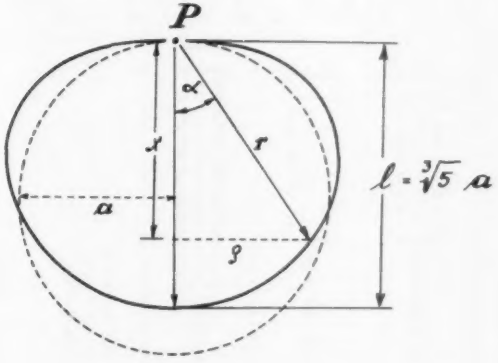
The maximum attraction at the pole of an oblate spheroid exceeds the attraction of a sphere of equal volume and density by about one part in 45 (McMillan, 1930, p. 65).

RÉSUMÉ

Table I presents a few formulae demonstrated in this paper. For sake of convenience, letter N indicates the numerical value of $2\pi \cdot k \cdot p$ where p is a factor which converts the results into milligals, i.e.,

if the distances are given in kilofeet, $N = 12.76233$,

if the distances are given in kilometers, $N = 41.87115$,



$$F_{max} = 2\pi \cdot \kappa \cdot \delta \int_0^l \left(1 - \frac{x}{\sqrt{x^2+\rho^2}}\right) dx \qquad [23]$$

$$= \frac{4}{5}\pi \cdot \kappa \cdot \delta \cdot l$$

FIG. 14. The maximum attraction of a figure of revolution of given volume and density exceeds the attraction of the sphere of equal volume and density by one part in 38 approximately.

TABLE I

GRAVITY ANOMALY FORMULAE FOR SOLIDS OF REVOLUTION

Solids of revolution	General formulae	Extreme cases	Glossary of terms:
Cone	$N\cdot\delta\cdot\left[l-(r_l-d)\cos^2\beta-d\cos\beta\cdot\sin^2\beta\cdot\ln\left\{\frac{r_l+H+d\cos\beta}{d+d\cos\beta}\right\}\right]$ Eq. (5)	*P on apex* $N\cdot\delta\cdot l(1-\cos\beta)$ Eq. (6) $\cos\beta=l/H$	$N=2\pi\cdot k.\mathrm{p}$ $=12.76$ (for distances in kilofeet) $=41.87$ (for distances in kilometers) δ=density (density contrast) p=factor to convert the results into milligals P=unit particle a=altitude of frustrum; radius of sphere c=distance between P and upper base of frustrum or inverted cone c, C=distance between P and point of intersection of axis on the spherical surface d=distance between P and apex of cone H=length of slope of cone l=altitude of cone and cap L=altitude of lower spherical segment r_u, r_l=distance between P and edge of (lower or upper) base of frustum r=distance between P and edge of segment R=distance between P and center of sphere ρ=radius of base $\cos\beta=l/H$ of cone $\cos\beta=l/r$ of cap
Inverted Cone	$N\cdot\delta\cdot\left[l-(d-r_u)\cos^2\beta-d\cos\beta\cdot\sin^2\beta\cdot\ln\left\{\frac{d+d\cos\beta}{r_u-H+d\cos\beta}\right\}\right]$ Eq. (9)	*P on base* $N\cdot\delta\cdot\frac{l\cdot\delta}{H^2}\left[l+\rho-\frac{l\cdot\rho}{H}\cdot\ln\left(\frac{l(H+l)}{\rho(H-\rho)}\right)\right]$ Eq. (9a)	
Frustrum and inverted frustrum	$N\cdot\delta\cdot\left[a-(r_l-r_u)\cos^2\beta-d\cos\beta\cdot\sin^2\beta\cdot\ln\left\{\frac{r_l\cdot\cos\beta-d\sin^2\beta+(a+c)}{r_u\cdot\cos\beta-d\sin^2\beta+c}\right\}\right]$ Eq. (7) & Eq. (10)	*Frustrum = Cylinder* $N\cdot\delta[a-(r_l-r_u)]$ Eq. (8) (Peirce, 1886)	
Cap (or upper spherical segment)	$N\cdot\delta\cdot\frac{2l^2(3a+c-r)}{3(c+r)^2}$ Eq. (13)	*P on vertex* $N\cdot\delta\cdot l\cdot(1-\frac{2}{3}\cos\beta)$ Eq. (14) $\cos\beta=l/r$	
Lower spherical segment	$N\cdot\delta\cdot\frac{2L^3(3a-C+r)}{3(C+r)^2}$ Eq. (15)	*P on base* $N\cdot\delta\frac{(a^3+R^3-\rho^3)}{3R^2}$ $R=L-a$ Eq. (16)	

in both cases the Newtonian constant was taken (after P. R. Heyl, 1926) as $k = 6.664 \times 10^{-8}$ cm^3 gr^{-1} sec^{-2}.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the kind help and valuable suggestions of Max Plotkin of Harvard University, Dr. S. Beatty of the University of Toronto, Dr. D. C. Skeels and J. T. Hughson of the Imperial Oil Company, and Dr. G. D. Garland of the University of Alberta in the course of the preparation of this paper.

REFERENCES

Dobrin, M. B., 1952, Introduction to geophysical prospecting: New York, McGraw-Hill Book Co., Inc.

Heiland, C. A., 1946, Geophysical exploration: New York, Prentice-Hall, Inc.

Heyl, P. R., 1927, A redetermination of the Newtonian constant; Proc. Nat. Acad. Sci., v. 13, p. 601–605.

Kellogg, O. D., 1929, Foundations of potential theory: New York, Dover Publications, Inc.

McMillan, W. D., 1930, The theory of the potential: New York, McGraw-Hill Book Co., Inc.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill Book Co., Inc.

Peirce, B. O., 1886, Elements of the theory of the Newtonian potential function: Boston, Ginn and Co.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 520–535, 7 FIGS.

RESULTS FOR A GRAVITY CONTROL NETWORK AT AIRPORTS IN THE UNITED STATES*

G. P. WOOLLARD†

ABSTRACT

Results are presented for a network of gravity control bases located at the major airports throughout the United States. This network of bases was established as a means of integrating existing gravity surveys into a unified whole. It provides not only control of data but also a means of checking and adjusting calibration differences to a common standard. The gravity standard used is that determined by measurements with the Gulf compound quartz pendulum apparatus at a series of sites covering a range of 4,800 mgals between Fairbanks, Alaska, and Mexico City, D. F., Mexico. The accuracy of the individual measurements on an absolute basis is believed to be within 0.3 mgal using a Potsdam datum value of g equal to 980.1190 gals taken at floor level in the United States Coast and Geodetic Survey gravity vault in the Commerce Building, Washington, D. C. Observation sites are described with sufficient detail to permit reoccupation within 5 to 6 feet.

INTRODUCTION

The integration of local gravity surveys into a unified network is important for many regional geophysical, geologic, and geodetic studies. The United States network of about 1,200 pendulum gravity bases established by the U. S. Coast and Geodetic Survey (Duerksen, 1949) for many years was felt to be adequate for this purpose, but as the need for a nation-wide precision of better than one mgal became desirable it was evident that these measurements did not have the requisite accuracy. Check observations over the past 25 years have shown considerable error in some values as well as systematic and base observation errors. Although work for any field season might have an average accuracy of ± 1 mgal on a station-to-station basis, the average absolute error might vary as much as 5 mgals from season to season (Woollard, Harding, and Rose, 1955). The United States Coast and Geodetic Survey is now systematically checking the pendulum network measurements, but it will be several years before all of the errors in the pendulum network can be completely evaluated. Many of the pendulum sites, furthermore, are now extremely difficult to find; some are inaccessible and many are inconveniently located for general use either as control points or for gravimeter standardization measurements. In view of these defects and the immediate need in several scientific studies for a control network of gravity bases having an accuracy of better than one mgal, the writer, under the auspices of the Cambridge Research Center of the U. S. Air Force, started building up an auxiliary network of gravity control bases in the United States in 1954. This program, which has now advanced to the point where the measurements are complete enough to be of practical value, can be divided into two parts. The first consists of pendulum measurements carried out with the compound quartz pendulum apparatus developed by the Gulf Research and Development Com-

* Manuscript received by Editor December 19, 1957.

† University of Wisconsin, Madison, Wisconsin.

pany which was loaned to the writer for this work. The second part consists of gravimeter measurements connecting the principal airports throughout the country. The pendulum measurements follow three North-South traverses and are primarily for overall control and the standardization of the gravimeters used in the more extensive airport base network. The present paper deals only with the airport network of bases. The pendulum results are to be presented as a separate paper.

Airports were chosen for the regional base sites because of their accessibility and general degree of permanence. Base sites at airports, which can be occupied during the few minutes a plane on a continuing flight is on the ground, also offer certain unique advantages for gravimeter work; instrumental drift can be held to a minimum, and an extensive series of measurements covering a large change in gravity or an area can be accomplished in a few hours with a minimum of expense by utilizing commercial air transportation.

OBSERVATIONAL PROGRAM AND REDUCTION OF DATA

The gravimeter observations were made using two high range geodetic type Worden gravity meters which were calibrated against the series of Gulf pendulum measurements between Fairbanks, Alaska, and Mexico City, Mexico (Bonini and Woollard, 1957). These measurements, which cover about 4,800 mgals change in gravity, permit a comprehensive evaluation of the linearity of response of the gravimeters as well as a superior calibration.

The location of airports between which connecting measurements were made is shown in Figure 1. In reducing the data, "drift" was determined on the basis of the net closure after removing overnight and layover change in instrument readings and the net closure distributed on the basis of actual transit operating time. This method of evaluating drift is believed by the writer to be more reliable than that which uses the drift rate observed during stopovers because of the sensitivity of the drift rate with Worden instruments to variations in temperature gradient. Particularly when using plane transportation, temperatures in transit are apt to be considerably different from those on the ground in either the summer or the winter, and also changes in ground climatic environment when covering large areas can be quite marked. This method of drift determination does not eliminate the problem of temperature shock, jumps in readings occasioned by sudden changes in temperature, or "tares" introduced by jars; but it does help keep the drift factor to a minimum.

BASE VALUE

While the United States Coast and Geodetic Survey has adopted a value of 980.118 gals for the United States national gravity base in the Department of Commerce building in Washington, D. C., this value on the basis of intercomparisons with other national gravity bases tied to the Potsdam, Germany, primary base should be closer to 980.119 gals (Woollard, 1950). In the interest of

FIG. 1. Measured intervals of the Airport Gravity Network.

international connections and overall global studies, the base value adopted for the present measurements is 980.1190 gals. This is the value at floor level in the gravity vault of the Coast and Geodetic Survey in the Department of Commerce Building and not on the piers which stand about one meter above floor level. The piers are no longer being used as an observation site because of apparent resonance effects discovered by the Coast and Geodetic Survey which it is believed were a major factor in causing the seasonal base errors found in the earlier pendulum measurements.

All field values in the present study have been determined on the basis of differences in gravity relative to the Commerce Building base in Washington. Actually several bases were used in Washington which had been interconnected. These are the Department of Commerce base (U.S.C. & G.S. Sta. 337), the Geophysical Laboratory of the Carnegie Institution of Washington (U.S.C. & G.S. Sta. 338), the Bureau of Standards absolute gravity site (U.S.C. & G.S. Sta. 84A), and the National Airport.

Since the pendulum observation site at each of the three locations is located in a building that is closed on weekends and in the evenings and cannot be entered at these times without special advance arrangements, an auxiliary outside station was established at each so that an effective connection could be made at any time. Similarly, at the Washington National Airport two sites were used, one at ground level on the field side of the terminal building and one on the street side of the terminal by one of the main entrances. The latter is desirable because of the difficulty of getting access to the field except during the period of actual arrival or departure.

Closures and interval measurements for the Washington network of stations are given in Table I and shown graphically in Figure 2. Station descriptions are given in Table II so that the above sites in Washington can be reoccupied. Check observations by other investigators between these sites indicate agreement to within 0.1 mgal with those of the writer (Hammer, 1947; Rice,[1] 1956).

AIRPORT NETWORK RESULTS

In presenting the results for the airport network of gravity bases two sets of interval values are shown; the first is the mean of the observed values, and the second is an adjusted value to give zero closure. The failure to obtain zero closure on each of the measured loops is related to the fact that some legs were measured several times and others only once. The sensitivity of the instruments, Worden geodetic gravimeters with a range of 3,000 and 5,000 mgals, was 0.1 and 0.2 mgal respectively. Although results are given to the nearest gravity unit (0.1 mgal), there is an uncertainty of about ± 0.1 mgal in those cases involving several measurements and about ± 0.2 mgal where there are only one or two measurements. The strongest network is in the eastern and midwestern areas, the weakest in the western states where more work is required.

[1] Personal communication.

(*Text continued on page 531*)

TABLE I

GRAVITY BASE NETWORK
INTERVAL MEASUREMENTS
WASHINGTON, D. C.

	Number of Observations and Average Value Mgals
U. S. National Base*—14th St. Gateway *Floor of gravity vault in basement of Commerce Bldg. Outside station on 14th St. side of Commerce Bldg.	− 0.8 (av. 6) mgal
14th St. Gateway—Geophysical Lab. Base* *Floor of basement compressor room main building.	−17.6 (av. 8) mgals
Geophysical Lab. Base—Outside Station* *Ground level SW corner of building.	− 0.7 (av. 4) mgal
Geophysical Lab. Outside—Bureau of Standards absolute site* *Floor level in sub-sub-basement room of East Bldg.	− 0.4 (av. 5) mgal
Bureau of Standards absolute base—outside station* *Foot of steps rear entrance to East Bldg.	− 1.9 (av. 4) mgals
Bureau of Standards Outside—Nat'l Airport field level	+12.3 (1) mgals
Nat'l Airport field level—Street side terminal	− 1.0 (av. 6) mgal
Nat'l Airport street side terminal—U. S. Nat'l Base	+10.1 (av. 4) mgals
Closure	0.0 mgals

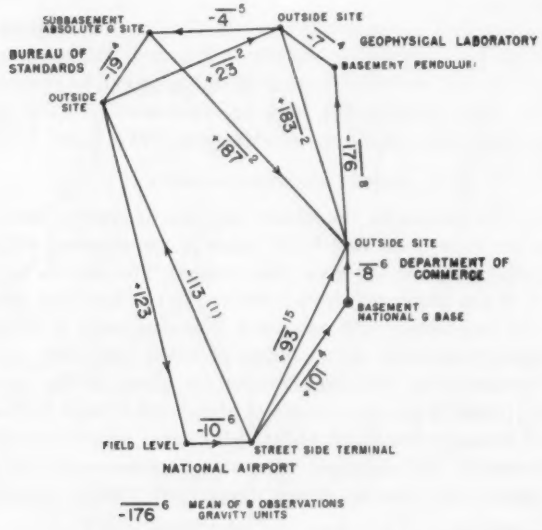


FIG. 2. Measured intervals of the Washington bases.

TABLE II

WASHINGTON, D. C. BASE SITES

Descriptions	*Gravity Value*
National Bureau of Standards, Connecticut Ave., N.W.	
On floor of sub-sub-basement room used for absolute gravity determination by Heyl and Cook in East Bldg. U.S.C. & G.S. Pendulum Sta. 84A	980.0995
Outside auxiliary site, foot of steps at rear entrance to East Bldg.	980.1099
Geophysical Laboratory, Carnegie Institution of Washington, 2801 Upton St., N.W.	
Basement compressor room, west end of building, U.S.C. & G.S. Pendulum Sta. 338 site. University of Wisconsin Pendulum Sta. site.	980.1006
Outside auxiliary site, ground level at SW corner of building (front corner parking lot side) by bench mark disk in wall.	980.0999
Department of Commerce Bldg., Constitution Ave.	
U.S.C. & G.S. Pendulum Sta. 337 site. Used as a national reference station.	
Floor of basement gravity vault off carpenter shop in U. S. Coast & Geodetic Survey wing.	980.1190
Outside auxiliary site on curb on left side of north gate archway of the 14th St. entrance to south motor car parking area; marked with a brass disk.	980.1182
Nat'l Airport	
Field level in center of terminal lobby bay to right of baggage truck entry 6 facing field outside Eastern Airlines air freight office.	980.1099
Auxiliary site, on porch to left of East entry to terminal lobby facing street at base of first column above which is letter "W" of word WASHINGTON.	980.1089

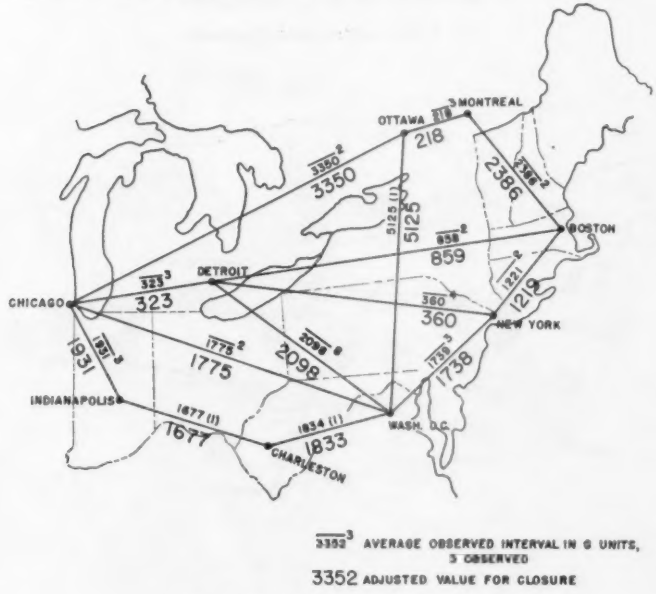


FIG. 3. Northeastern control network.

FIG. 4. Southeastern control network.

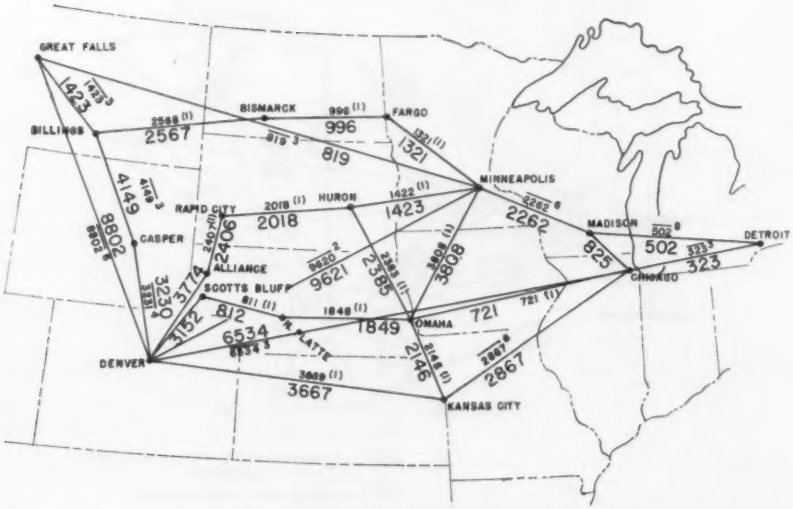


FIG. 5. North Central control network.

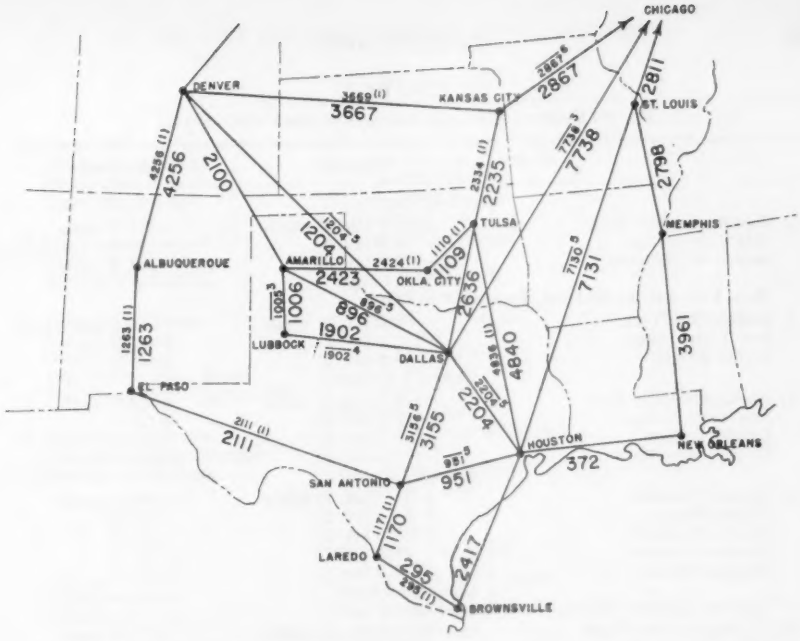


FIG. 6. South Central control network.

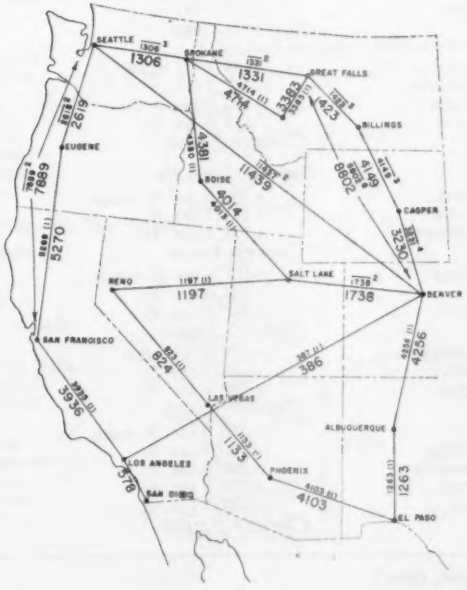


FIG. 7. Western control network.

TABLE III

GRAVITY CLOSURE NETS FOR AIRPORTS IN THE UNITED STATES

	Observed	Adjusted
	Northeast Closure Net	
1. Washington–New York*	+173.9 (av. 3) mgals	+173.8 mgals
New York–Detroit	+ 36.0 (av. 4)	+ 36.0
Detroit–Washington	−209.8 (av. 8)	−209.8
	Closure 0.1 mgal	
*New York LaGuardia Field, Terminal Post Office.		
2. Detroit–New York	− 36.0 (av. 4) mgals	− 36.0 mgals
New York–Boston	+122.1 (av. 2)	+121.9
Boston–Detroit	− 85.8 (av. 2)	− 85.9
	Closure 0.3 mgal	
3. Washington–New York	+173.9 (av. 3) mgals	+173.8 mgals
New York–Boston	+122.1 (av. 2)	+121.9
Boston–Chicago	−118.1 (av. 2)	−118.2
Chicago–Washington	−177.6 (av. 2)	−177.5
	Closure 0.3 mgal	
4. Chicago*–Detroit	+ 32.3 (av. 2) mgals	+ 32.3 mgals
Detroit–Boston	+ 85.8 (av. 2)	+ 85.9
Boston–Montreal	+238.6 (av. 2)	+238.6
Montreal–Ottawa	− 21.8 (av. 3)	− 21.8
Ottawa–Chicago	−335.0 (av. 3)	−335.0
	Closure 0.1 mgal	
*Chicago Midway Airport, North Central Airline Lobby.		
5. Washington–New York*	+173.9 (av. 3) mgals	+173.8 mgals
LaGuardia-Boston	+122.1 (av. 2)	+121.9
Boston–Montreal	+238.6 (av. 2)	+238.6
Montreal–Ottawa	− 21.8 (av.)	− 21.8
Ottawa–Washington	−512.5 (1)	−512.5
	Closure 0.3 mgal	
*New York LaGuardia Field, Terminal Post Office.		
6. Washington–Charleston	−183.4 (1) mgals	−183.3 mgals
Charleston–Indianapolis	+167.7 (1)	+167.7
Indianapolis–Chicago	+193.1 (av. 3)	+193.1
Chicago–Washington	−177.6 (av. 2)	−177.5
	Closure 0.2 mgal	
	Southeast Closure Net	
1. Washington–Atlanta	−588.6 (av. 9) mgals	−588.6 mgals
Atlanta–Jacksonville	−134.7 (av. 6)	−134.8
Jacksonville–Washington	+723.4 (av. 3)	+723.4
	Closure 0.1 mgal	
2. Washington–Chicago	+177.6 (av. 2) mgals	+177.5 mgals
Chicago–Atlanta	−766.0 (av. 3)	−766.1
Atlanta–Washington	+588.6 (av. 9)	+588.6
	Closure 0.2 mgal	
3. Washington–Birmingham	−570.0 (1) mgals	−570.0 mgals
Birmingham–Atlanta	− 18.6 (av. 2)	− 18.6
Atlanta–Washington	+588.6 (av. 9)	+588.6
	Closure 0.0 mgal	
4. Chicago–Atlanta	−766.0 (av. 3) mgals	−766.1 mgals
Atlanta–New Orleans	−190.9 (av. 4)	−190.9
New Orleans–Memphis	+396.0 (av. 2)	+396.1
Memphis–St. Louis*	+279.8 (av. 4)	+279.8
St. Louis–Chicago	+281.1 (av. 5)	+281.1
	Closure 9.9 mgals	

* Municipal Airport, Gate 2.

TABLE III (*continued*)

	Observed	Adjusted
5. Atlanta–Birmingham	+ 18.6 (av. 2) mgals	+ 18.6 mgals
Birmingham–Louisville	+419.6 (1)	+419.6
Louisville–Atlanta	−438.2 (1)	−438.2
	Closure 0.0 mgal	
6. Washington–Charlotte	−380.8 (1) mgals	−380.8 mgals
Charlotte–Atlanta	−207.8 (1)	−207.8
Atlanta–Washington	+588.6 (av. 9)	+588.6
	Closure 0.0 mgal	
7. Jacksonville–Tampa	−181.3 (1) mgals	−181.3 mgals
Tampa–Orlando	+ 14.5 (1)	+ 14.4
Orlando–Miami	−165.1 (1)	−165.1
Miami–West Palm Beach	+ 79.2 (1)	+ 79.2
West Palm Beach–Jacksonville	+252.8 (1)	+252.8
	Closure 0.1 mgal	
8. Atlanta–Jacksonville	−134.7 (av. 5) mgals	−134.8 mgals
Jacksonville–New Orleans	− 56.1 (1)	− 56.1
New Orleans–Atlanta	+190.9 (av. 4)	+190.9
	Closure 0.1 mgal	
	North Central Closure Net	
1. Chicago*–Detroit	+ 32.3 (av. 3) mgals	+ 32.3 mgals
Detroit–Madison	+ 50.2 (av. 8)	+ 50.2
Madison–Chicago	− 82.5 (av. 7)	− 82.5
	Closure 0.0 mgal	
*Chicago Midway Airport, North Central Airline Lobby.		
2. Chicago–Kansas City	−286.7 (av. 6) mgals	−286.7 mgals
Kansas City–Omaha	+214.5 (1)	+214.6
Omaha–Chicago	+ 72.1 (1)	+ 72.1
	Closure 0.1 mgal	
3. Omaha–Minneapolis	+380.8 (1) mgals	+380.8 mgals
Minneapolis–Huron	−142.2 (1)	−142.3
Huron–Omaha	−238.5 (1)	−238.5
	Closure 0.1 mgal	
4. Chicago–Madison*	+ 82.5 (av. 7) mgals	+ 82.5 mgals
Madison–Minneapolis	+226.2 (av. 6)	+226.2
Minneapolis–Omaha	−380.8 (1)	−380.8
Omaha–Chicago	+ 71.9 (1)	+ 72.1
	Closure 0.2 mgal	
*University of Wisconsin Base Station.		
5. Minneapolis–Fargo	+132.1 (1) mgals	+132.1 mgals
Fargo–Bismark	− 99.6 (1)	− 99.6
Bismark–Billings	−256.8 (1)	−256.7
Billings–Great Falls	+142.3 (av. 3)	+142.3
Great Falls–Minneapolis	+ 81.9 (av. 3)	+ 81.9
	Closure 0.1 mgal	
6. Minneapolis–Great Falls	− 81.9 (av. 3) mgals	− 81.9 mgals
Great–Falls–Denver	−880.2 (av. 6)	−880.2
Denver–Minneapolis	+962.0 (av. 2)	+962.1
	Closure 0.1 mgal	
7. Chicago–Madison	+ 82.5 (av. 7) mgals	+ 82.5 mgals
Madison–Minneapolis	+226.2 (av. 6)	+226.2
Minneapolis–Great Falls	− 81.9 (av. 5)	− 81.9
Great Falls–Denver	−880.2 (av. 6)	−880.2
Denver–Chicago	+653.4 (av. 4)	+653.4
	Closure 0.0 mgal	

TABLE III (*continued*)

	Observed	Adjusted
8. Denver–Casper	+323.1 (av. 4) mgals	+323.0 mgals
Casper–Billings	+414.9 (av. 4)	+414.9
Billings–Great Falls	+142.3 (av. 3)	+142.3
Great Falls–Denver	−880.2 (av. 6)	−880.2
	Closure 0.1 mgal	
9. Denver–Scotts Bluff	+315.1 (1) mgals	+315.2 mgals
Scotts Bluff–North Platte	+ 81.1 (1)	+ 81.2
North Platte–Omaha	+184.8 (1)	+184.9
Omaha–Chicago	+ 72.1 (1)	+ 72.1
Chicago–Denver	−653.4 (av. 4)	−653.4
	Closure 0.3 mgal	
10. Denver–Alliance	+377.4 (1) mgals	+377.4 mgals
Alliance–Rapid City	+240.7 (1)	+240.6
Rapid City–Huron	+201.8 (1)	+201.8
Huron–Minneapolis	+142.2 (1)	+142.3
Minneapolis–Denver	−962.0 (av. 2)	−962.1
	Closure 0.1 mgal	
11. Denver–Chicago	+653.4 (av. 3) mgals	+653.4 mgals
Chicago–Kansas City	−286.7 (av. 6)	−286.7
Kansas City–Denver	−366.9 (1)	−366.7
	Closure 0.2 mgal	
	South Central Closure Net	
1. Houston–Dallas	+220.4 (av. 5) mgals	+220.4 mgals
Dallas–Chicago	+773.8 (av. 3)	+773.8
Chicago–St. Louis	−281.1 (av. 5)	−281.1
St. Louis–Houston	−713.0 (av. 5)	−713.1
	Closure 0.1 mgal	
2. Dallas–Kansas City	+487.1 (av. 3) mgals	+487.1 mgals
Kansas City–Chicago	+286.7 (av. 6)	+286.7
Chicago–Dallas	−773.8 (av. 3)	−773.8
	Closure 0.0 mgal	
3. Houston–New Orleans	+ 37.2 (av. 5) mgals	+ 37.2 mgals
New Orleans–Memphis	+396.0 (av. 2)	+396.1
Memphis–St. Louis	+279.8 (av. 4)	+279.8
St. Louis–Houston	−713.0 (av. 5)	−713.1
	Closure 0.0 mgal	
4. Dallas–San Antonio	−315.6 (av. 5) mgals	−315.5 mgals
San Antonio–Houston	+ 95.1 (av. 5)	+ 95.1
Houston–Dallas	+220.4 (av. 5)	+220.4
	Closure 0.1 mgal	
5. Dallas–Denver	+120.4 (av. 5) mgals	+120.4 mgals
Denver–Kansas City	+366.9	+366.7
Kansas City–Dallas	−487.1	−487.1
	Closure 0.2 mgal	
6. Houston–San Antonio	− 95.1 (av. 6) mgals	− 95.2 mgals
San Antonio–Dallas	+315.6 (av. 5)	+315.6
Dallas–Tulsa	+263.6 (1)	+263.6
Tulsa–Houston	−483.6 (1)	−484.0
	Closure 0.5 mgal	
7. Dallas–Amarillo	− 89.6 (av. 5) mgals	− 89.6 mgals
Amarillo–Denver	+210.1 (av. 5)	+210.0
Denver–Dallas	−120.4 (av. 5)	−120.4
	Closure 0.1 mgal	
8. Dallas–Lubbock	−190.2 (av. 4) mgals	−190.2 mgals
Lubbock–Amarillo	+100.5 (av. 3)	+100.6
Amarillo–Dallas	+ 89.6 (av. 5)	+ 89.6
	Closure 0.1 mgal	

TABLE III (*continued*)

	Observed	Adjusted
9. Houston–San Antonio	− 95.1 (av. 5) mgals	− 95.1 mgals
San Antonio–Laredo	−117.1 (1)	−117.0
Laredo–Brownsville	− 29.5 (1)	− 29.5
Brownsville–Houston	+241.6 (1)	+241.6
	Closure 0.1 mgal	
10. Dallas–Amarillo	− 89.6 (av. 5) mgals	− 89.6 mgals
Amarillo–Oklahoma City	+242.2 (1)	+242.3
Oklahoma City–Tulsa	+111.0 (1)	+110.9
Tulsa–Dallas	−263.6 (1)	−263.6
	Closure 0.2 mgal	
11. Houston–Denver	+340.8 (av. 5) mgals	+340.8 mgals
Denver–El Paso	−551.9 (1)	−551.9
El Paso–Houston	+211.1 (1)	+221.1
	Closure 0.0 mgal	
	Western Closure Net	
1. Denver–Great Falls	+880.2 (av. 6) mgals	+880.2 mgals
Great Falls–Spokane	+133.1 (av. 2)	+133.1
Spokane–Seattle	+130.6 (av. 3)	+130.6
Seattle–Denver	−1143.7 (av. 2)	−1143.9
	Closure 0.2 mgal	
2. Great Falls–Spokane	+133.1 (av. 2) mgals	+133.1 mgals
Spokane–Butte	−471.4 (1)	−471.4
Butte–Great Falls	+338.4 (1)	+338.3
	Closure 0.1 mgal	
3. Denver–Great Falls	+880.2 (av. 6) mgals	+880.2 mgals
Great Falls–Spokane	+133.1 (1)	+133.1
Spokane–Boise	−438.0 (1)	−438.1
Boise–Salt Lake	−401.3 (1)	−401.4
Salt Lake–Denver	−173.8 (av. 2)	−173.8
	Closure 0.2 mgal	
4. Seattle–Eugene	−261.8 (1) mgals	−261.9 mgals
Eugene–San Francisco	−526.9 (1)	−527.0
San Francisco–Los Angeles	−393.5 (1)	−393.6
Los Angeles–Denver	+ 38.7 (1)	+ 38.6
Denver–Great Falls	+880.2 (av. 6)	+880.2
Great Falls–Seattle	+263.7 (av. 2)	+263.7
	Closure 0.4 mgal	
5. Denver–Salt Lake City	+173.8 (av. 2) mgals	+173.8 mgals
Salt Lake City–Reno	−119.7 (1)	−119.7
Reno–Las Vegas	− 82.3 (1)	− 82.4
Las Vegas–Phoenix	−113.3 (1)	−113.3
Phoenix–El Paso	−410.3 (1)	−410.3
El Paso–Albuquerque	+126.3 (1)	+126.3
Albuquerque–Denver	+425.6	+425.6
	Closure 0.1 mgal	

Obviously the strength of this control net will increase with time as more observations are taken. A caution should be given in this connection, however, in that all instruments used for long runs must be on the same calibration standard, that based on measurements with the Gulf pendulum apparatus. While the calibration method and standards used by the manufacturers of gravimeters are more than adequate for assuring high precision measurements of small changes in gravity, they are inadequate for evaluating a change of 1,000 mgals to within 0.5

(*Text continued on page 535*)

TABLE IV

GRAVITY VALUES AIRPORT BASES

Based on U.S.C. & G.S. STATION 337 980.119 (Potsdam datum)

CANADA	
Montreal, Quebec—Barrier gate opposite center of terminal lobby bay	980.6432
Ottawa, Ontario—At terminal lobby entrance from field	980.6214
Toronto—Outside field entrance to Canadian Customs for incoming passengers	980.4299
Winnipeg—Ground level at street entrance to terminal lobby	980.9927
MEXICO	
Monterrey, Nuevo Leon—At entrance American Airlines terminal lobby from field	978.8613
UNITED STATES	
Alabama	
Birmingham—Barrier, Gate 5	979.5389
Mobile—Bates Field, center gate in barrier	979.3392
Muscle Shoals—Center gate in barrier	979.6912
Arizona	
Phoenix—Barrier, Gate 3	979.4914
Tucson—Barrier, Gate 4	979.2272
Arkansas	
Little Rock—Barrier, Gate 1	979.7243
California	
Fresno—Barrier, Gate 2	979.8325
Los Angeles—International Airport, street side of United Airlines lobby to left of street exit	979.5944
Merced—Telephone booth at barrier in front of terminal	979.9000
San Diego—Inside terminal lobby at street entrance middle door	979.5366
San Francisco—International Airport, Gate 23–24 to field in Concourse C.	979.9880
Colorado	
Colorado Springs—Barrier gate opposite terminal lobby entrance	979.4830
Denver—Telephone booth opposite barrier, Gate 2	979.6330
District of Columbia	
Washington (See Table II for description)	
Dept. of Commerce—Gravity Vault	980.1190
Dept. of Commerce—Outside auxiliary site	980.1182
Geophysical Laboratory—Basement	980.1006
Geophysical Laboratory—Outside auxiliary site	980.0999
National Bureau of Standards—Sub-basement	980.0995
National Bureau of Standards—Outside auxiliary site	980.0976
National Airport—Field level	980.1099
National Airport—Street side of terminal	980.1089
Florida	
Daytona Beach—Center gate in barrier	979.2778
Gainesville—Center gate in barrier	979.3062
Jacksonville—Barrier, Gate 6	979.3855
Miami—Eastern Airlines Terminal, Gate 1 to field East Concourse	979.0535
Ocala—Center gate in barrier	979.2614
Orlando—Barrier, Gate 3	979.2186
Pensacola—Barrier, Gate 3	979.3626
Sarasota—Center gate in barrier	979.2440
St. Petersburg—At outside baggage claim stand	979.1969
Tallahassee—Center gate in barrier	979.3540
Tampa—Base of terminal building control tower	979.2042
West Palm Beach—Barrier, Gate 2	979.1327
Georgia	
Atlanta—(Old terminal) Gate 1 to field in east concourse	979.5203
Brunswick—Center gate in barrier	979.4494
Columbus—Terminal lobby entrance from field	979.5122
Macon—Center gate in barrier	979.5320
Savannah—Barrier, Gate 2 by outside baggage claim stand	979.4977

Idaho	
Boise—In foyer of entrance to terminal lobby from field	980.2082
Illinois	
Chicago—Midway Airport (lobby N. Central Airlines)	980.2864
Chicago—O'Hare Airport Concourse B, Gate 2 exit to field	980.2894
Springfield—Street entrance to terminal lobby	980.0820
Indiana	
Indianapolis—Barrier, Gate 5	980.0933
Lafayette—In waiting room Purdue Univ. hangar opposite field exit	980.1468
Iowa	
Cedar Rapids—At barrier right side of terminal facing field	980.2519
Des Moines—Beneath marquee 50 ft from terminal lobby door	980.1984
Kentucky	
Louisville—Barrier, Gate 12	979.9585
Louisiana	
New Orleans—Barrier, Gate 5	979.3294
Shreveport—Barrier, Gate 1	979.5302
Massachusetts	
Boston—Logan Field—Amer. Airlines lobby Gate 19 exit	980.4038
Boston—Logan Field—Northeast Airlines lobby, Gate 14 exit	980.4046
Michigan	
Detroit—Willow Run Airport Gate 17 in Blue Concourse	980.3187
Minnesota	
Mankato—Entrance to terminal baggage room	980.4667
Minneapolis—In Concourse, Gate 1 exit	980.5951
Rochester—Barrier, Gate 1	980.4312
Mississippi	
Jackson—Barrier, Gate 4	979.5267
Missouri	
Kansas City—Street entrance to terminal lobby sidewalk level	979.9997
St. Louis—Old Terminal—Barrier, Gate 1	980.0053
St. Louis—New Terminal—Gate 2W, Concourse exit to field	980.0040
Montana	
Billings—In air freight shed, next to terminal building	980.3709
Butte—Outside terminal room at barrier	980.1740
Cutbank—At terminal lobby entrance from field	980.6085
Great Falls—Inside terminal lobby left of exit to field	980.5132
Helena—Barrier gate opposite terminal lobby entrance	980.3778
Kalispell—Inside terminal lobby right of exit to field	980.5819
Missoula—Inside terminal lobby right of exit to field	980.4438
Nebraska	
Alliance—Barrier gate opposite terminal lobby entrance	980.0104
Grande Island—Center gate in barrier; new terminal	980.0956
Lincoln—Alcove outside of field entrance to terminal lobby	980.1756
North Platte—Barrier gate opposite terminal lobby entrance	980.0294
Omaha—Outside of field entrance to terminal lobby	980.2143
Scotts Bluff—Barrier gate opposite terminal lobby entrance	979.9482
Nevada	
Ely—At barrier gate opposite terminal lobby entrance	979.4943
Las Vegas—Center point of terminal lobby	979.6047
Reno—Barrier, Gate 6	979.6871
Tonopah—Barrier gate opposite terminal lobby entrance	979.4764
New Hampshire	
Lebanon—Barrier gate opposite terminal lobby entrance	980.4413
New Jersey	
Wrightstown—McGuire Air Force Base; MATS terminal lobby left entrance from field	980.2127
New Mexico	
Albuquerque—Beneath terminal entrance marquee at barrier	979.2074
Alamagordo—Entrance to Bldg. 282	979.1479
Santa Fe—Right of terminal lobby entrance from field	979.1970

New York	
New York—Idlewild Airport—In corridor opposite exit from Customs (Old Terminal)	980.2273
New York—LaGuardia Airport—Lower lobby of terminal at Post Office counter	980.2827
New York—LaGuardia Airport—Field level American Airlines to Gate 4 in Area B Lobby	980.2831
Syracuse—Barrier, Gate 2	980.3965
North Carolina	
Charlotte—Entrance to terminal lobby from concourse for Gates 10–16 (New Terminal)	979.7281
Greensboro—Base of terminal building control tower	979.7656
New Bern—Entrance to terminal lobby from field	979.7284
Raleigh-Durham—Barrier Gate 2	979.8016
Wilmington—Center gate in barrier	979.6769
North Dakota	
Bismarck—Terminal lobby entrance from field	980.6276
Fargo—In foyer of terminal lobby entrance from field	980.7272
Jamestown—at barrier opposite terminal lobby entrance	980.6542
Ohio	
Cincinnati—Barrier Gate 3	979.9929
Cleveland—Concourse Gate 6 exit to field	980.2325
Columbus—Barrier Gate 3	980.0773
Oklahoma	
McAlester—At barrier opposite terminal lobby entrance	979.6271
Oklahoma City—At entrance to terminal lobby from field	979.6653
Tulsa—Barrier Gate 3	979.7762
Oregon	
Eugene—Beneath marquee at terminal lobby entrance	980.5150
Medford—Beneath marquee opposite Gate 3	980.2363
Pendleton—North Gate in barrier	980.5118
Portland—Barrier Gate 3	980.6482
Salem—At barrier opposite terminal lobby entrance	980.5838
Pennsylvania	
Pittsburgh—Barrier Gate 9-A	980.0994
South Carolina	
Charleston—Air Force Base, MATS Terminal lobby	979.5671
Charleston—Barrier Gate 4 Civil Airport	979.5664
Florence—At barrier opposite terminal lobby entrance	979.6848
Greenville—At base of terminal building control tower	979.6229
South Dakota	
Aberdeen—At central gate in barrier	980.5439
Brookings—At barrier opposite entrance to terminal lobby	980.4303
Hot Springs—Barrier gate in front of terminal lobby entrance	980.1954
Huron—West corner of terminal building—Ground level	980.4528
Huron—Basement of terminal (Pendulum site)	980.4537
Rapid City—At entrance to terminal lobby from field	980.2510
Spearfish—Barrier gate in front of terminal lobby entrance	980.2521
Tennessee	
Memphis—Barrier Gate 9	979.7255
Nashville—Entrance to terminal lobby from field	979.7794
Texas	
Amarillo—Right of terminal lobby entrance from field	979.4230
Brownsville—Barrier Gate 1	979.0505
Corpus Christi—On runway to left of field entrance to terminal lobby	979.1430
Dallas—Barrier Gate 12	979.5126
El Paso—Beneath marquee at terminal lobby entrance	979.0811
Ft. Worth—Gate 1–2 Concourse entrance from field	979.4930
Houston—Barrier Gate 4 (Old Terminal)	979.2922
Houston—Base of fire plug below restaurant bay (new terminal)	979.2928
Laredo—Building T-204	979.0801
Lubbock—Barrier Gate 3	979.3224
San Antonio—Barrier Gate 8 (U. S. Customs, incoming entrance)	979.1971
Tyler—On field 50 ft out from center barrier gate	979.4779
Wichita Falls—At barrier beneath marquee	979.5480

Utah	
Ogden—At barrier opposite terminal entrance	979.8176
Salt Lake City—Inside terminal center door leading to field	979.8068
Vermont	
Burlington—Barrier Gate 2	980.5273
Montpelier—At center barrier gate	980.4630
Virginia	
Richmond—Barrier Gate 1, New Terminal	979.9533
Washington	
Seattle—Inside field entry, Gate 5, to terminal	980.7769
Spokane—At fireplace, center of terminal lobby	980.6463
Walla Walla—At North gate in barrier	980.5741
West Virginia	
Charleston—Barrier Gate 6	979.9256
Wisconsin	
LaCrosse—Barrier gate opposite terminal entrance	980.4568
Madison—Truax Field inside terminal opposite street entrance	980.3725
Madison—Science Hall, Basement hall at entrance to Rm. 7 (Pendulum site) (Pendulum site, Rm. 26—980.3687)	980.3689
Milwaukee—Inside South concourse Gate 1-6 at field level	980.3597
Wyoming	
Casper—Barrier Gate 3	979.9560
Cheyenne—Center barrier gate	979.7000
Sheridan—Center barrier gate	979.2263

mgal, and in some cases to within even 10 mgals (see Woollard and Bonini, 1955).

In Table III the results for the country are presented and divided on a regional basis into the northeast sector, southeast sector, north central sector, south central sector, and western sector. On the same basis the results are shown graphically in Figures 3, 4, 5, 6, and 7.

DESCRIPTION OF SITES

To avoid lengthy descriptions all observations were made at ground level on the field side of airport terminals at the field barrier, unless otherwise noted. In the table of final values of observed gravity, Table IV, the barrier gate numbers and other pertinent information are given. It is believed these descriptions will suffice to permit the original observation sites to be recovered to within 5 or 6 ft. Where terminals were obviously temporary structures, the term "old terminal" indicates the site is associated with a structure that has been or is likely to be superseded by a new building.

REFERENCES

Bonini, W. E., and Woollard, G. P., 1957, The observation accuracy of high range geodetic type Worden gravimeter: Trans. Amer. Geophys. Un., v. 38, p. 147–155.

Duerksen, J. A., 1949, Pendulum gravity data in the United States: Washington, U. S. Coast and Geodetic Survey, Special Publication 244.

Hammer, Sigmund, 1947, Gravimetric ties between gravity base stations in Washington, D. C.: Trans. Amer. Geophys. Un., v. 28, p. 157–161.

Woollard, G. P., 1950, The gravity meter as a geodetic instrument: Geophysics, v. 15, p. 1–29.

———, and Bonini, W. E., 1955, A review of the factors affecting the accuracy of long-distance and intercontinental gravimeter measurements: Trans. Amer. Geophys. Un., v. 36, p. 575–583.

Woollard, G. P., Harding, N. C., and Rose, J. C., 1955, The problem of calibrating high range geodetic type gravimeters: Trans. Amer. Geophys. Un., v. 36, p. 12–24.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 536–556, 13 FIGS.

NUMERICAL RESISTIVITY ANALYSIS: HORIZONTAL LAYERS*

KEEVA VOZOFF†

ABSTRACT

The direct numerical solution of resistivity data for the case of horizontal layering is presented as the solution of a set of nonlinear algebraic equations. Two specific methods, Newton and Steepest Descent, were set up for three-layer analyses on a digital computer. These were applied to field data and to data derived theoretically for three- and four-layer cases.

The case of a thin second layer was found to display a special kind of indeterminacy. It was found that the analyses do not and cannot theoretically be expected to yield the actual values of resistivity and thickness for these thin layers, but, rather, a good value for their ratio (conductive layer) or product (resistive layer) can be obtained. The question of ultimate resolubility of this type of information in the presence of measurement error is discussed quantitatively. It was found that, as the resistivity of the third (lowermost) layer increases, it becomes increasingly difficult to detect a thin, resistive second layer. When the second layer is not thin relative to the first, the resistivities and thicknesses are determined with reasonable accuracy. These solutions do not appear to be unique, but alternate solutions differ sufficiently for the true solution to be easily distinguished.

INTRODUCTION

The satisfactory interpretation of resistivity data, even in the relatively simple case of horizontal layering, is at present a very difficult task. There are two main reasons for this difficulty. The first is that the mathematical problem itself is so complex, and it thus requires elaborate analytical methods. The other is that insufficient numerical work has been carried out on existing analytical methods to evaluate their effectiveness. There is no real knowledge of what can be done with resistivity data. An objective quantitative analytical technique, applicable under general layering conditions and making full use of the accuracy of the data, would be of great aid to our understanding.

Most interpretation, at the present time, is done by visual comparison of observed data with groups of curves calculated theoretically. This curve matching is undoubtedly the most convenient of analyses, but it has severe limitations. The greatest of these is the small number of cases which are represented by curves, and it is, therefore, impossible to use the full accuracy of the data. As shown below, this allows a very wide choice of possible solutions, especially when lower layers are thinner than those above. Several sets of curves have been published of various functions which can be used for interpretation (apparent resistivities, potentials, etc.) of which the most recent are by Schlumberger (1955) and Mooney and Wetzel (1956).

Numerous methods of interpretation have been presented and applied by Langer (1933), Slichter (1933), and Stevenson (1934) for the case of a *continuous* vertical variation of resistivity. These methods do not deal with field data directly, but rather with a function which is more simply related to the resistivity

* This material is a portion of a Ph.D. thesis submitted by the author to the Massachusetts Institute of Technology. Manuscript received by the Editor January 13, 1958.

† 970 Eglinton Avenue, East, Toronto 17, Ontario, Canada.

variation, the Slichter kernel. In this case it is assumed that the resistivity $\rho(z)$ can be expressed as a power series in z (the depth), whose coefficients are determined by comparison with the coefficients of the kernel, also expressed in power series. The kernel must be obtained from the field data through an integration. Due to the complex algebraic relationships which exist between the two sets of coefficients, the methods are extremely cumbersome. If a discontinuity in resistivity exists, the power series, and therefore the methods, break down. A later modification of the method of Langer (1936) was able to handle the case of a single discontinuity, and Stevenson treated a case of two discontinuities with reasonable success.

A graphical-numerical method was devised by Pekeris (1940) for analysis of the Slichter kernel in the case of horizontal layering. The method works quite well, subject only to the restriction that each layer be thicker than the one above it.

The method presented here is also an analysis of the Slichter kernel, in which one must assume the number of layers. Under this assumption, the kernel is expressible as a closed, non-integral function of the layer thicknesses and resistivities. By assuming initial values of these parameters and then changing them slowly, one is able to fit this calculated kernel to that integrated from the field data. The closeness of fit obtainable depends upon the degree of resemblance between actual and assumed geology and upon the accuracy of the measurements and the integration.

The guidance of T. R. Madden of the Massachusetts Institute of Technology is gratefully acknowledged.

FORMULATION OF THE PROBLEM

In the direct interpretation problem one starts by assuming a physical model of the earth which is usually considerably simpler than the true situation. The model (see Figure 1) consists of a number (n) of horizontal homogeneous, isotropic

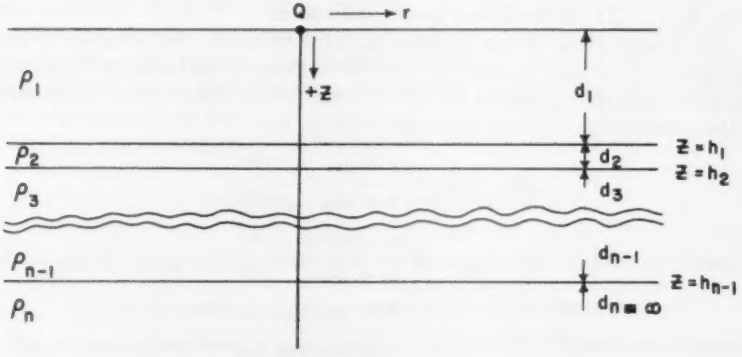


FIG. 1. Physical model assumed for analysis.

layers. The typical (i-th) layer has resistivity ρ_i and thickness d_i. The bottom layer is of resistivity ρ_n and thickness d_n.

For a (hypothetical) point source of current (Q), a radially symmetric potential, $\phi(r, z)$, is set up in the medium.

The method has several desirable features: It utilizes the full accuracy of the measurements; it is objective; it is essentially automatic; and it is completely general requiring no assumptions regarding the layering. On the other hand, the amount of computation involved almost necessitates the use of expensive high-speed computers.

The "fitting" approach used here is very general and has, potentially, a much wider range of application of geophysical problems. (In theory any criterion of curve fitting can be used; in practice the simplest is usually least squares.) Strickland,* for example, analyzed gravity anomalies using an absolute value fit in a method of linear programming.

This potential must conform to the usual boundary conditions, i.e.,

$$\text{(a)}\quad \phi(r, z) \to 0 \quad \text{as} \quad r \to \infty \quad \text{or} \quad z \to \infty\,;$$

at the interface between adjacent layers

$$\text{(b)}\qquad \phi_i(r, h_i) = \phi_{i+1}(r, h_i)$$

$$\text{(c)}\quad \rho_{i+1} \frac{\partial \phi_i(r, h_i)}{\partial z} = \rho_i \frac{\partial \phi_{i+1}(r, h_i)}{\partial z}$$

and ϕ must remain finite for $r=0$, $z>0$. The solution to this boundary value problem is well known. The only portion which is of interest here is that on the surface, because it corresponds to the quantities measured in the field. The expression for surface potential is

$$\phi(r, 0) \equiv \phi(r) = \frac{\rho_1}{2\pi} \int_0^\infty k_{12\cdots n}(\lambda) J_0(\lambda r) d\lambda \tag{1}$$

where $k_{12\cdots n}(\lambda)$ is the kernel mentioned above.

The actual value of the Slichter kernel depends on the number of layers and the values of their parameters, but the solution of the boundary value problem gives a general expression for the function. This is most conveniently written in the substitution notation of Sunde (1949, p. 54)

$$\begin{aligned} k_{12\cdots n}(\lambda) &= \frac{1 - \mu_{12\cdots n} e^{-2\lambda d_1}}{1 + \mu_{12\cdots n} e^{-2\lambda d_1}} \\ \mu_{12\cdots n} &= \frac{\rho_1 - \rho_2 k_{23\cdots n}(\lambda)}{\rho_1 + \rho_2 k_{23\cdots n}(\lambda)} \\ k_{(m-1)m\cdots n}(\lambda) &= \frac{1 - \mu_{(m-1)m\cdots n} e^{-2\lambda d_{m-1}}}{1 + \mu_{(m-1)m\cdots n} e^{-2\lambda d_{m-1}}} \end{aligned} \tag{2}$$

* Personal communication.

$$\mu_{(m-1)m\cdots n} = \frac{\rho_{m-1} - \rho_m k_{(m+1)\cdots n}(\lambda)}{\rho_{m-1} + \rho_m k_{(m+1)\cdots n}(\lambda)}.$$

$$\mu_{(n-1)n} = \frac{\rho_{n-1} - \rho_n}{\rho_{n-1} + \rho_n}.$$

Where possible in this paper, the abbreviation will be used

$$l_i = e^{-2\lambda d_i}.$$

It is the kernel corresponding to the measured potentials which is analyzed, and this is obtained uniquely by a Hankel inversion of equation (1), viz.

$$k(\lambda) = \frac{\lambda}{\rho_1}\int_0^\infty r\phi(r)J_0(\lambda r)dr. \tag{3}$$

The parameter λ has no direct physical significance. Comparison of the kernel and potential shows a correspondence in behaviour of $k(\lambda)$ at large λ with $\phi(r)$ at small r, and vice versa, which is expected from their mathematical relationship. The importance of this relationship in the analysis will be discussed in the section on computation.

It is seen that the Slichter kernel can be (a) derived from field data by integration of equation (3), or (b) calculated algebraically from a set of assumed parameters by equations (2). The method of analysis presented here starts with the assumption of a given number of layers and the values of their parameters. These are used to calculate a kernel by method (b). Small changes are then made in the assumed values of thicknesses and resistivities so as to make this kernel fit more closely the kernel calculated from the field measurements by (a). This process is repeated and it is then assumed that the final values of the parameters in this procedure are the desired solution. Mathematically speaking, this may or may not be true, i.e., whereas a perfect fit undoubtedly indicates one solution to the problem, there is no reason to believe that there are not other solutions. Indeed, experience with the method indicates that more than one solution does exist, but the physical requirements on the solution (positive and real ρ_i and d_i) certainly reduce the number of allowable solutions. In addition, the freedom of choice allowed in the first estimates enables one to direct the solution to the right neighborhood, at least.

The least squares statement of the problem, then, is to minimize

$$\sum_{j=1}^{m} [k_{12\cdots n}(\lambda_j) - k_f(\lambda_j)]^2 \equiv K \tag{4}$$

with respect to the ρ_i and d_i, where k_f is the kernel integrated from field data.

ALTERNATIVE SOLUTIONS AND LIMITS OF SOLUBILITY

The problem as set forth in equation (4) is to solve a set of nonlinear algebraic (i.e., non-integral) equations. Several methods are described in the literature,

two of which were applied to this problem. These were the method of Functional Iteration or Newton's Method (von Sanden, 1923; Householder, 1953) and the Method of Steepest Descent (Householder). The derivations of the equations used will be reserved for the Appendix. The final equations and a description of the processes will be given below.

It will be noted that, in the case of n layers, there are $2n-3$ unknowns: $n-1$ thicknesses and $n-2$ resistivities. The resistivity of the top and bottom layers can be found directly from the field data, as they are the limits of apparent resistivities for small and large spreads, respectively.

The Functional Iteration Method (FIM)

This method (for $2n-3$ unknowns) follows quite closely Newton's technique for finding roots of a nonlinear equation in a single unknown. The shortcomings of the procedure are discussed in some detail by Hildebrand (1949). An initial estimate is made of the values of the roots, and it is assumed that this estimate is quite close to the true values. If only small changes are to be made, the function can be approximated by the first two terms of its Taylor expansion in these unknown parameters. This expansion is then used to calculate the changes necessary in the initial estimates, and the process is repeated until no further changes are indicated.

If $k_{12\cdots n}(\lambda j)$ is calculated for $2n-3$ values of j, one can write

$$k_{12\ldots n}(\lambda_j) - k_f(\lambda_j) = \epsilon_j$$

for every j.

To reduce all errors to zero, one sets

$$\Delta k_{12\ldots n}(\lambda_j) = \epsilon_j^*$$

which, when combined with the approximate expansion, gives

$$\Delta k_{12\ldots n}(\lambda_j) = \sum_{a=1}^{2n-3} \frac{\partial k(\lambda_j)}{\partial p_a} \Delta p_a. \tag{10}$$

Here, p_a is generalized notation for the parameters ρ_i and d_i. Since there are a like number of equations and unknowns, the errors can be reduced identically to zero by sufficient repetition of the process.

Unfortunately, none of the values of $k_f(\lambda_j)$ are without measurement error. In order to reduce the effect of individual errors, a modification is introduced which utilizes an excess of data, i.e., $m > 2n-3$, and minimizes the quantity.

$$\sum_{j=1}^{m} [\epsilon_j - \Delta k_{12\ldots}(\lambda_j)]^2 \tag{5}$$

which is similar but not identical to equation (4). The difference is that equation

* Note that $\sum_{j=1}^{m} \epsilon_j^2 = K$.

(5) attempts to minimize the difference between the error and the change in the error, whereas equation (4) attempts to minimize the error itself. The former is a rather unusual criterion, but it was necessary for the statement of the solution (6) in its relatively simple form.

The solution equations are

$$\sum_{b=1}^{2n-3} \Delta p_b \sum_{j=1}^{m} \left[\frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_a} \frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_b} \right] = \sum_{j=1}^{m} \epsilon_j \frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_a}, \qquad (6)$$

$$a = 1, 2, \cdots, 2n-3,$$

a set of $2n-3$ linear equations in the same number of unknowns from which the Δp can be found in a straightforward manner. These Δp are then used to calculate second guesses ($p_a^1 = p_a^0 + \Delta p_a$) and the process repeated. It is seen that equations (6) can be rewritten in matrix notation as

$$[s_{ab}]\{p_b\} = \{g_a\} \qquad (6a)$$

where

$$s_{ab} = s_{ba} = \sum_{j=1}^{m} \left[\frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_a} \frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_b} \right]$$

$$g_a = \sum_{j=1}^{m} \epsilon_j \frac{\partial k_{12\cdots n}(\lambda_j)}{\partial p_a}.$$

This more systematic form allows the possible computational difficulties of the method to be studied more easily than does equation (6). It is seen, for instance, that the matrix solution can run into trouble in the case of degeneracy or near degeneracy (an excess number of assumed layers giving arbitrary derivatives or parameter values), or in the case where, at any point in the iterative procedure, one of the parameters is much farther than another from solution, giving derivatives differing by orders of magnitude.

The Steepest Descent Method (SDM)

The SDM is possibly simpler in conception than the FIM and appears to be more satisfactory in application. It deals directly with the function K of equation (4), which can be thought of as an error function, $K(p_a)$. If one takes as a first estimate of the p_a the true values of all but one, and then changes that one noting the change in $K(p_a)$, it will be observed that $K(p_a)$ will generate a smooth curve. If the variable is changed in the direction of its true value, $K(p_a)$ will become smaller until it reaches a minimum (near the true value of the variable p_a) and then start to increase. The same behavior will be observed for any of the p_a. Two variables would generate a true surface of K, etc.

The process of steepest descent is most readily visualized in the two-variable case, although it is the same mathematically in any number of variables. The

first estimates of the p_a correspond to some point on the K-surface. The gradient of K is calculated at this point, and the p_a are changed in the proper proportion so as to descend along this initial gradient vector. Because of surface undulations, it is unlikely that this initial direction extends through the actual minimum, but the p_a can be changed until the minimum of K *in that direction* is reached. At this point a new gradient must be calculated and another descent made. The process must be repeated until a point of zero gradient is reached or until K becomes smaller than some predetermined value. (A verbal description of the SDM is also given in Householder (1953), p. 132.)

It is ordinarily impossible to predict exactly the amounts by which the p_a should be changed in a particular descent. Conceivably, small stepwise changes could be made along the gradient until a minimum is reached, but this is a very slow process. Numerical extrapolation of a Newton type was considered to be more practical. The actual extrapolation evolved into a fairly satisfactory two-stage procedure which is described in the Appendix. Stated formally, the problem is to choose M in the equation

$$K(p_a^{(h+1)}) = K\left[p_a^{(h)} - M \frac{\partial K}{\partial p_a} \Big/ |\operatorname{grad} K|\right] \tag{7}$$

so as to minimize $K(p_a^{(h+1)})$. The superscript serves as an iteration index.

There is no mathematical guarantee that the minimum obtained will be the only one, nor is it possible to say how many minima exist: Experience indicates that there may be more than one. Many possibilities can be ruled out by the requirement of real and positive p_a, but each solution must be examined to see if it is reasonable. If not, the starting point was probably within the influence of a secondary minimum, and another starting point must be selected.

Limits of Solubility

In the course of applying these methods, it was observed that certain three-layer resistivity situations, nominally quite different, had kernels which were identical, to a first approximation. This situation arose in the cases of thin second layers of resistivity either much higher or much lower than that of the top and bottom layers. It is quite easily shown that, with a thin second layer ($d_2 \ll d_1$), and $\rho_2 \to \infty$ such that

$$d_2\rho_2 = c_1 = \text{constant}$$

$$f_{123}(\lambda) \to \frac{t_1}{2} \frac{\rho_1 - \rho_3 - c_1\lambda}{\rho_1 + \rho_3 + c_1\lambda}$$

and $f_{122}(\lambda)$ is independent of the individual values of ρ_2 and d_2. Here

$$f_{123}(\lambda) = \frac{1}{1 + k_{123}(\lambda)} - \frac{1}{2}. \tag{8}$$

Likewise, if $\rho_2 \to 0$ such that

$$\frac{d_2}{\rho_2} = c_2 = \text{constant}$$

$$f_{123}(\lambda) \to \frac{t_1}{2} \frac{\rho_1 - \rho_3 + \rho_1\rho_3 c_2\lambda}{\rho_1 + \rho_3 + \rho_1\rho_3 c_2\lambda}$$

and $f_{123}(\lambda)$ depends only of the ratio d_2/ρ_2. A great increase in data accuracy is required to distinguish between cases of identical c_1 or c_2. Fortunately, the problem seldom arises as such in practice. From the point of view of the analyst, however, it indicates the wide range of possible solutions in these cases.

The effectiveness of an analysis can be considered in terms of its ability to distinguish between two nearly identical cases. This ability is limited by the accuracy of the data, and a numerical study was made to define these limits for normal measurement error (one percent). The study was directed, in particular, towards the detectability of a thin second layer beneath a relatively thick surface layer.

This was done by comparing two cases, the first of two layers

$$\rho_1 = d_1 = 1$$
$$d_2 = 0$$
$$d_3 = \infty$$

and the second of three layers

$$\rho_1 = d_1 = 1$$
$$d_3 = \infty$$

and

$$d_2\rho_2 = c_1 \quad \text{or} \quad d_2/\rho_2 = c_2,$$

as appropriate. Let

$$f_{13}(\lambda) - f_{123}(\lambda) = \Delta f(\lambda)$$

and $\epsilon_f(\lambda)$ be the errors in individual values of Δf due to measurement error. If it can be assumed that the condition

$$\sum_{i=1}^{m} \Delta f^2(\lambda_i) > \sum_{i=1}^{m} \epsilon_f^2(\lambda_i)$$

is necessary to enable the analysis to differentiate between the two nearly identical cases, it can be shown that

$$c_1^2 \sum_i \left[\frac{t_1\lambda_i^2}{\rho_1 + \rho_2 + c_1\lambda_i}\right]^2 > \frac{\Delta^2}{16\rho_1^2} \sum_i [\rho_1 + \rho_3 - (\rho_1 - \rho_3)t_1]^2$$

for $\rho_2 \to \infty$

and

$$c_2^2 \sum_i \left[\frac{t_1\lambda_i}{\sigma_1+\sigma_2+c_2\lambda_i}\right]^2 > \frac{\Delta^2}{16\rho_2^2}\sum_i [\rho_1+\rho_2-(\rho_1-\rho_2)t_1]^2$$

for $\rho_2 \to 0$

are *sufficient* conditions for resolution. The Δ is the maximum relative error in f, and $\sigma_i = 1/\rho_i$. Using the same values of λ as were used in the analysis of theoretical kernels ($\lambda = 1.0, 0.6, 0.4, 0.2, 0.1, 0.06, 0.04, 0.02, 0.01, 0.006$) and $\Delta = 0.01$, the minimum values of c_1 and c_2 calculated for various ρ_2 are given in Table I. It is seen that with f accurate to one percent, a conductive layer cannot be distinguished if $\rho_2 < 10^{-3}$, and a resistive layer cannot be distinguished if $\rho_2 > 10^3$. An increase of data accuracy to 0.1 percent would extend this range of ρ_2 by roughly a factor of ten at each end, i.e., from $\rho_2 > 10^{-4}$ to $\rho_2 < 10^4$.

TABLE I

MINIMUM VALUES OF c_1 AND c_2 NECESSARY TO ALLOW RESOLUTION OF A THIN INTERMEDIATE LAYER

ρ_2	c_1	c_2
10^{-3}	10^{-3}	Impossible
10^{-2}	10^{-2}	170
10^{-1}	1.4×10^{-2}	1.5
1.0	9.6×10^{-2}	9.6×10^{-2}
10^{1}	5.5	4.6×10^{-2}
10^{2}	3.3×10^{2}	4.1×10^{-2}
10^{3}	Impossible	4.1×10^{-2}

COMPUTATION RESULTS

Programs to perform the analysis were written for the MIT Whirlwind digital computer. Availability of computation time was made possible by the Office of Naval Research. The programs were designed for the three-layer case ($n = 3$) with the object of studying the general behavior of the analyses, the effect of excess layers, random errors, and the non-ideal conditions encountered in the field.

In most cases, ten values of λ ($m = 10$) were used. Several hundred kernels were calculated on Whirlwind, using expressions (2). Others, including apparent resistivity data from the field, were made available through the kindness of Mr. E. E. Maillot of Douglas, Arizona.

All kernels were normalized to $\rho_1 = 1$, and the theoretical kernels to $d_1 = 1$. Input data were:

(a) the number and values of λj
(b) values of ρ_1 and ρ_3
(c) the $k(\lambda j)$
(d) estimates of ρ_2, d_1, d_2.

The computer recorded and presented the values of ρ_2, d_1, d_2, and K resulting from each iteration. Operation was completely automatic, calculations ceasing only when K reached some small preset value or began to oscillate. The analysis dealt with the function $f(\lambda)$ rather than $k(\lambda)$ because the former is slightly simpler algebraically.

The role played by λ is perhaps worthy of some comment. It is, in a sense, equivalent to the wave number of hyperbolic equations, and it has also the dimensions of inverse length. Due to nature of the oscillations in the function $J_0(\lambda r)$, the major contribution to the Slichter kernel

$$k(\lambda) = \lambda \int_0^\infty r\phi(r) J_0(\lambda r) dr$$

is from small values of the argument (λr). For large λ, the region of small r is dominant. As λ decreases, the behavior at larger r becomes increasingly important, but never more important than that at small r. This is expected from the nature of the physical problem. One could probably increase the accuracy of analysis of deeper features by using more of the small λ, although this was never tried.

Regarding the range of λ to be used in analysis, examination of the curves in Figures 3 and 7 shows that the kernels are nearly constant at large and small λ but vary considerably in some intermediate range. The constant values are determined solely by ρ_1 and ρ_3 which are known from the apparent resistivities. It is the range in which $k(\lambda)$ is rapidly varying that should be analyzed.

RESULTS AND DISCUSSION

With the FIM some 30 cases were analyzed, including five integrated from field measurements, two derived from the four-layer formula and the remainder from the three-layer formula. It was believed that the thin second-layer case would be the most critical test of the methods, so that most of the effort was concentrated on this situation. The SDM was programmed to see if it would handle those cases in which FIM had difficulty; it was probably more successful because it is more straightforward. Some of the results of the two methods are presented in Figures 3–13.

A complete SDM solution is shown in Figure 2, as printed out by the computer. Each line containing four numbers is the result of a complete iteration. In order, the numbers are ρ_2, d_2, d_1, and K. The two-digit numbers following the slash indicate the exponent of ten. The top row contains the true values of the parameters, and the second row shows the first estimates which were fed into the computer. The remaining details are discussed in the Appendix. Comparison of lines 1, 2, and 6 shows that, although K has been reduced considerably, ρ_2 and d_2 have overshot. In the next iteration the solution is forced to backstep, and K increases again. Several iterations are required for the descent to recover from

ρ_2		d_2	d_1	$K(\xi_m)$ ρ_1	ρ_0	
+1.0000/ -01		+9.9999/ -03	+9.9999/ -01	+9.9999/ -01	+5.000/ -00	TRUE VALUES
+5.0000/ -02		+1.0000/ -01	+1.3999/ +00	+7.307/ -02		FIRST ESTIMATES
+7.6/ -05	Θ_1					
+2.7/ -03	Θ_2					
+1.284/ +00	c					
+2.1295/ -01		-6.2728/ -02	+1.3568/ +00	+1.034/ -04	FIRST ITERATION	
+9.5/ -05	Θ_1					
+9.8/ -05	Θ_2					
+3.863/ +02	c					
+6.8670/ -01		-5.3563/ -01	+3.5125/ +00	+3.744/ -02	SECOND ITERATION	
+5.6/ +08	Θ_1					
+7.9/ +05	Θ_2					
+3.744/ -01	c					
+4.5068/ -02		+9.3221/ -02	+7.1077/ -01	+7.118/ -02	THIRD ITERATION	
+7.4/ -02	Θ_1					
+2.7/ -04	Θ_2					
+8.577/ -01	c					
+1.1629/ -01		+2.2125/ -02	+7.1380/ -01	+1.746/ -03	FOURTH ITERATION	
+2.5/ -03	Θ_1					
+1.6/ -04	Θ_2					
+5.680/ -01	c					
+1.0480/ -01		+3.3590/ -02	+7.5295/ -01	+5.108/ -06	FIFTH ITERATION	
+5.7/ -06	Θ_1					
+4.8/ -06	Θ_2					
+4.227/ -01	c					
+1.1950/ -01		+1.9781/ -02	+9.2963/ -01	+9.275/ -08	SIXTEENTH ITERATION	
+9.5/ -08	Θ_1					
+9.2/ -08	Θ_2					
+4.319/ -01	c					
+1.1949/ -01		+1.9770/ -02	+9.2969/ -01	+9.167/ -08	SEVENTEENTH ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					
+1.195/ +00	c					
+1.1948/ -01		+1.9767/ -02	+9.2972/ -01	+9.158/ -08	EIGHTEENTH ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					
+6.253/ -01	c					
+1.1949/ -01		+1.9766/ -02	+9.2973/ -01	+9.149/ -08	NINTEENTH ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					
+4.978/ -01	c					
+1.1949/ -01		+1.9765/ -02	+9.2976/ -01	+9.156/ -08	TWENTIETH ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					
+7.17/ -01	c					
+1.1950/ -01		+1.9763/ -02	+9.2977/ -01	+9.140/ -08	TWENTY-FIRST ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					
+4.13/ -01	c					
+1.1950/ -01		+1.9762/ -02	+9.2978/ -01	+9.146/ -08	TWENTY-SECOND ITERATION	
+9.1/ -08	Θ_1					
+9.1/ -08	Θ_2					

Fig. 2. Computer output data for steepest descent iteration.

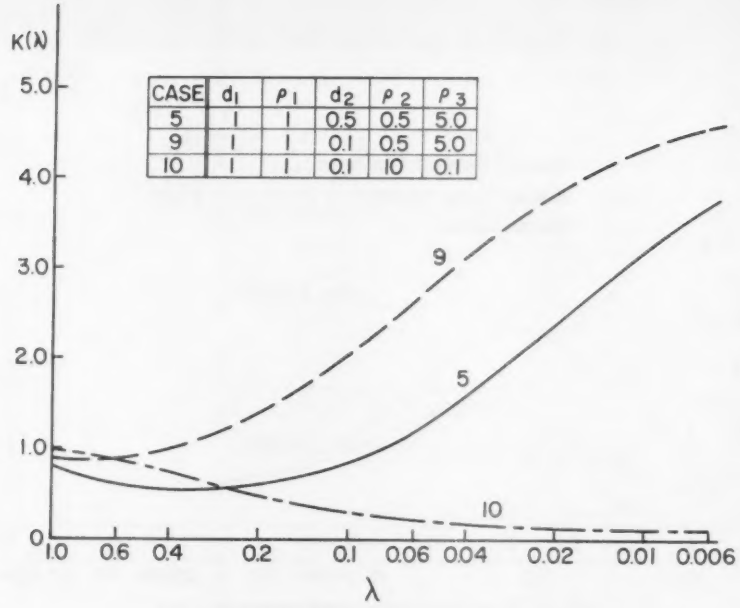


FIG. 3. Slichter kernels for three layers (Cases 5, 9, 10).

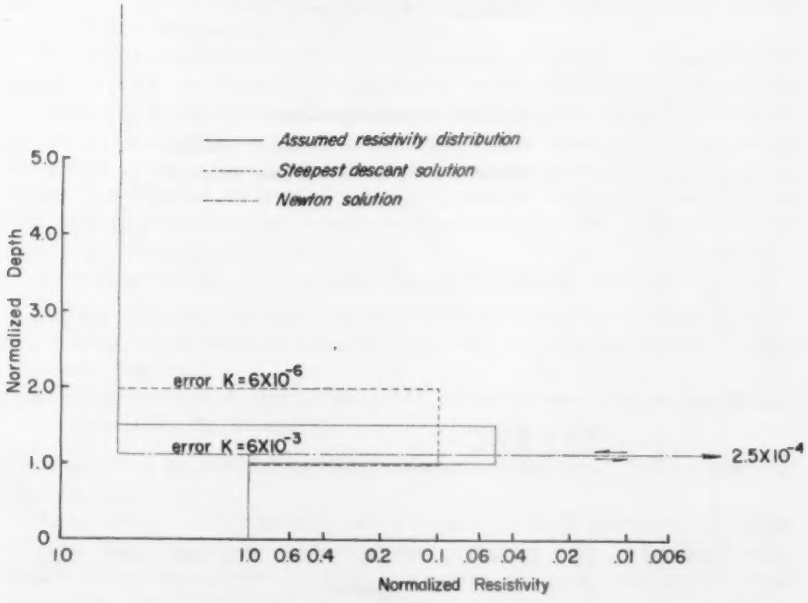


FIG. 4. Three-layer solutions, with assumed resistivity (Case 5). (K is the sum of squares of errors in least square fit at 10 points.)

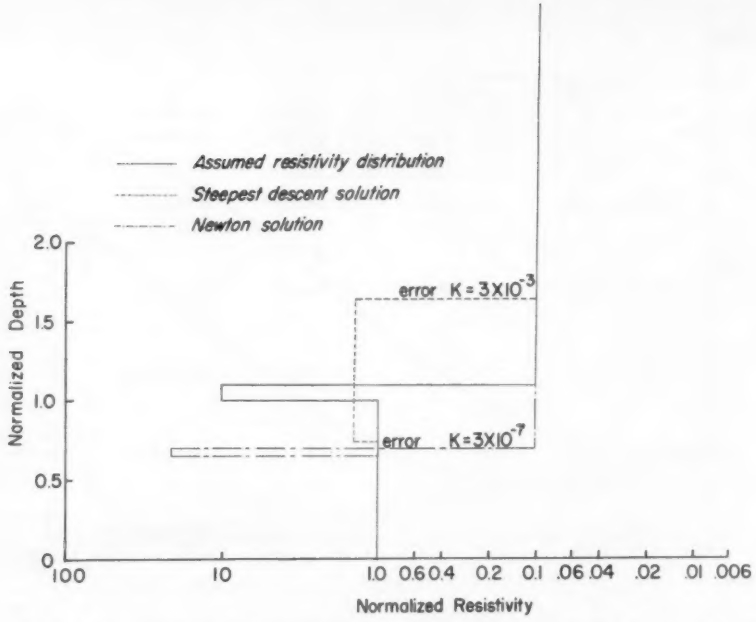


FIG. 5. Three-layer solutions, with assumed resistivity (Case 10). (K is the sum of squares of errors in least square fit at 10 points.)

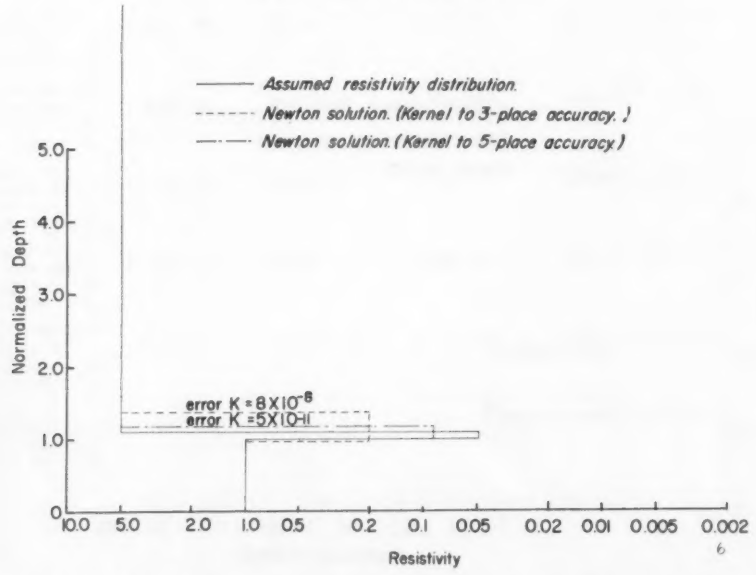
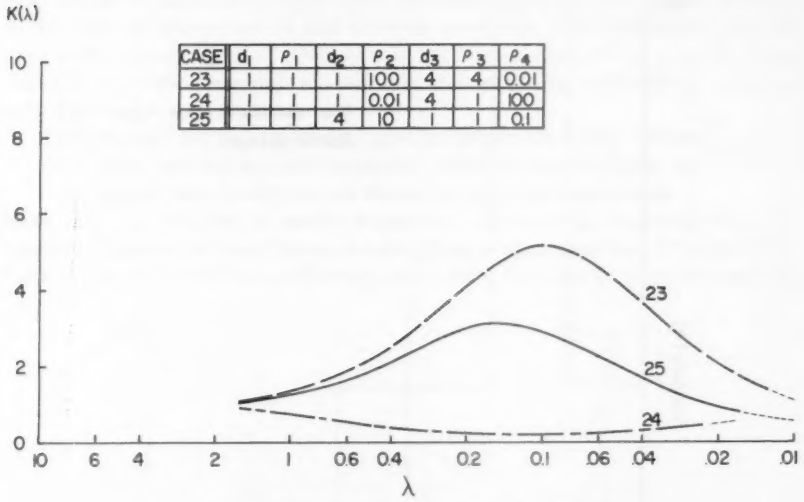


FIG. 6. Three-layer solutions, with assumed resistivity (Case 9). (K is the sum of squares of errors in least square fit at 10 points.)



CASE	d_1	ρ_1	d_2	ρ_2	d_3	ρ_3	ρ_4
23	1	1	1	100	4	4	0.01
24	1	1	1	0.01	4	1	100
25	1	1	4	10	1	1	0.1

FIG. 7. Slichter kernels for four layers (Cases 23, 24, 25).

the shock of the first estimates. This behavior is fairly typical. The entire process required about 4.5 minutes of computer time.

Success of an analysis, in the case of a theoretical kernel, is measured by the smallness of the final value of K obtained. In the thin second-layer situation, the closeness of c_1 or c_2 (as appropriate) to the true value can also be used as a measure of success. The minimum significant value of K was known for all analyses of theoretical kernels, since these kernels were calculated to seven places of accuracy and rounded off for analysis. With roundoff to three places the K of minimum significance in all cases was about 10^{-6}, for four places, 10^{-5}, etc. Figures 3–6 show some three-layer cases.

Several factors appear to influence the results. Among these are:

(a) For a complete solution (i.e., d_2 and ρ_2 individually correct) it was necessary that d_2 be larger than, say, $d_1/4$, and the larger the better, as might be expected.

(*b*) Improvement of data accuracy will ordinarily result in a better solution (compare cases 9a and 9b).

There appear to be other factors which influence the results to a lesser extent, but these are not all known.

An interesting point is brought out by a glance at the K values resulting from the three-layer analyses of four-layer kernels in Figures 7–10. Although the sampling is very poor, it is seen that these three values are of the order of 10^{-4}. Considering that the accuracy of most field measurements is about one percent, a

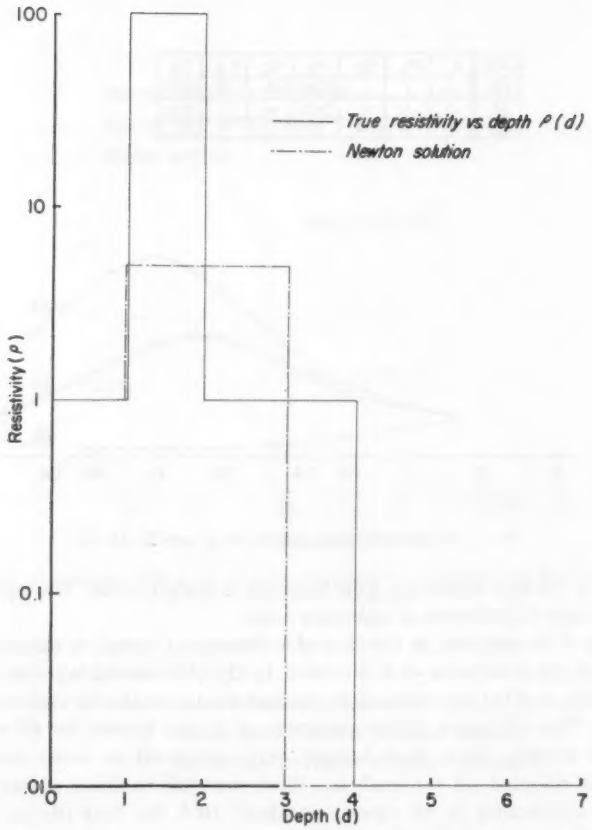


FIG. 8. Three-layer analysis of four-layer kernel (Case 23).

minimum significant K between 10^{-3} and 10^{-4} is obtained. Thus, it may be that with normal field accuracy, one can ask for no more than a three-layer approximation to the actual solution. However, a definite statement to this effect cannot be made until a four-layer solution is tried. It will be noted that, whereas these analyses give a solution in which the second and third layers appear to be smoothed together, the value of c_1 or c_2 (as applicable) obtained is characteristic of the second layer only.

Little can be said in general with regard to the five field cases. (Figures 11–13). None of the apparent resistivity curves (Figure 11) give the necessarily smooth appearance of theoretical cases.* The solutions (Figure 13) yield large d_2, and

* There appears to be at least a small amount of lateral variation in all.

thus would be expected to give quite satisfactory results with either FIM or SDM. Two of these cases (B and C) were done with both techniques, and the results were nearly identical. Drill data in the form of drillers logs exist for Cases A and B, but these are seldom of assistance in determining conductivity variation with depth.

Case A could not be expected to give satisfactory solution because

(a) $r\phi(r)$ had not reached a constant value at large r (Figure 11)

(b) lateral variations exist, as shown by other measurements.

Note that the solution is nearly degenerate, since $\rho_2 \approx \rho_3$, implying that the boundary location between layers two and three is very uncertain. K ranges from a maximum of 2×10^{-4} to a minimum of 3×10^{-7}, for Case D. This last had the

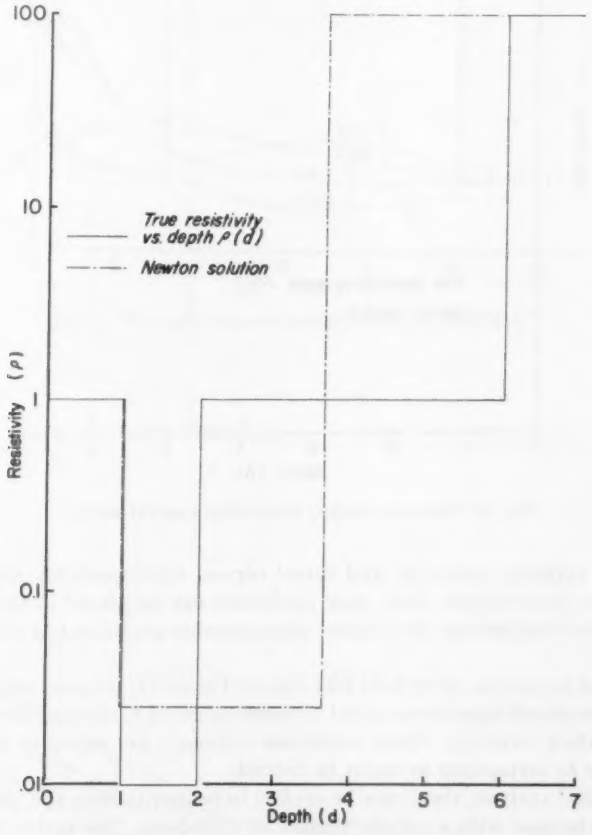


FIG. 9. Three-layer analysis of four-layer kernel (Case 24).

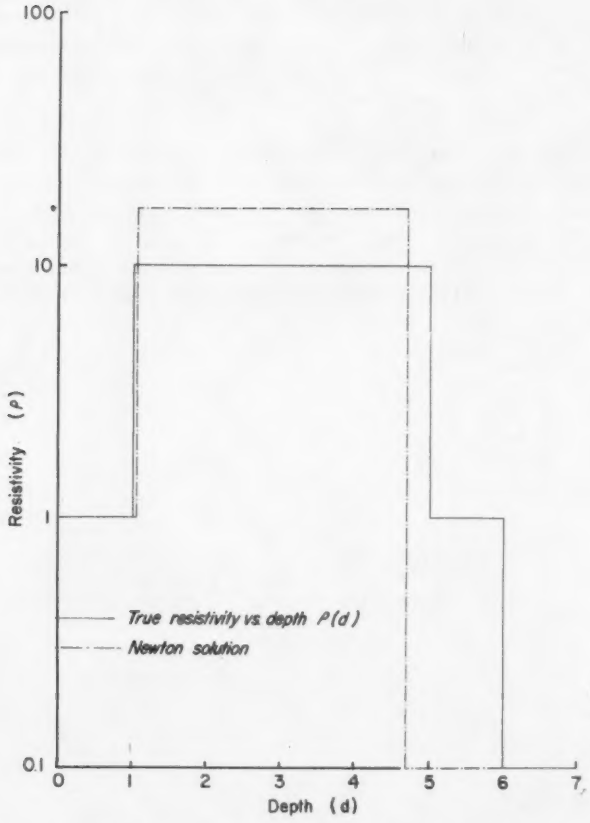


FIG. 10. Three-layer analysis of four-layer kernel (Case 25).

smoothest apparent resistivity and kernel curves, which probably explains the small error. Nevertheless, little more confidence can be placed in this solution than in the others because the original measurements are subject to the same errors.

From an inspection of the field $k(\lambda)$ curves (Figure 12) it would seem that the integrations should have been carried to larger values of λ, allowing better definition of shallow structure. These curves are obviously not extended as close to their (large λ) asymptotes as might be desired.

Numerical analysis, then, may be applied to resistivity data and gives results which can be used with a certain amount of confidence. The major limitations of the analyses lie in the nature of the physical and geological problems. To com-

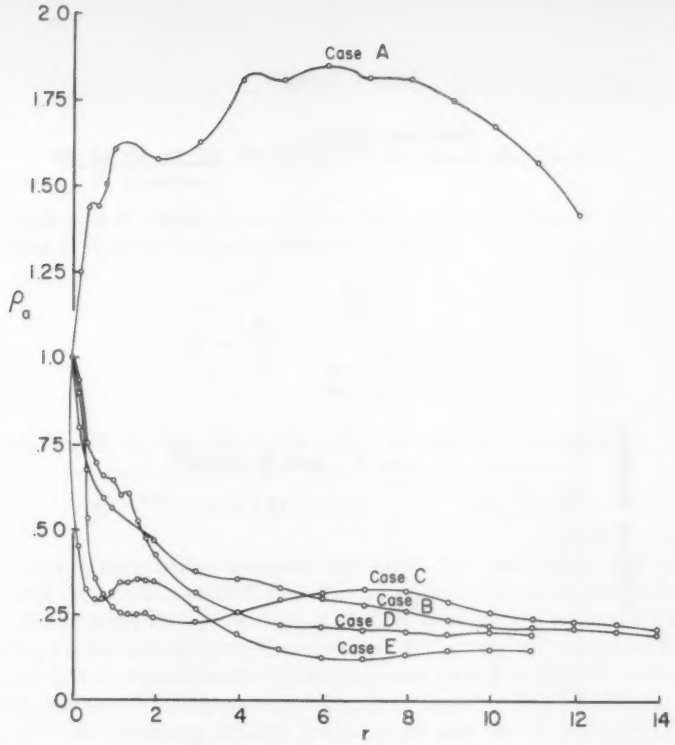


FIG. 11. Normalized apparent resistivities (Field Cases A–E).

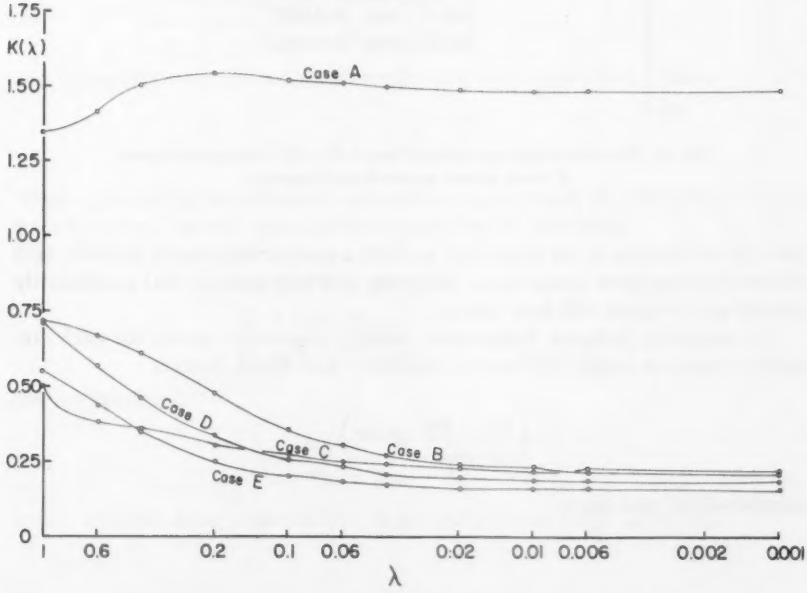


FIG. 12. Slichter kernels integrated from potentials (Field Cases A–E).

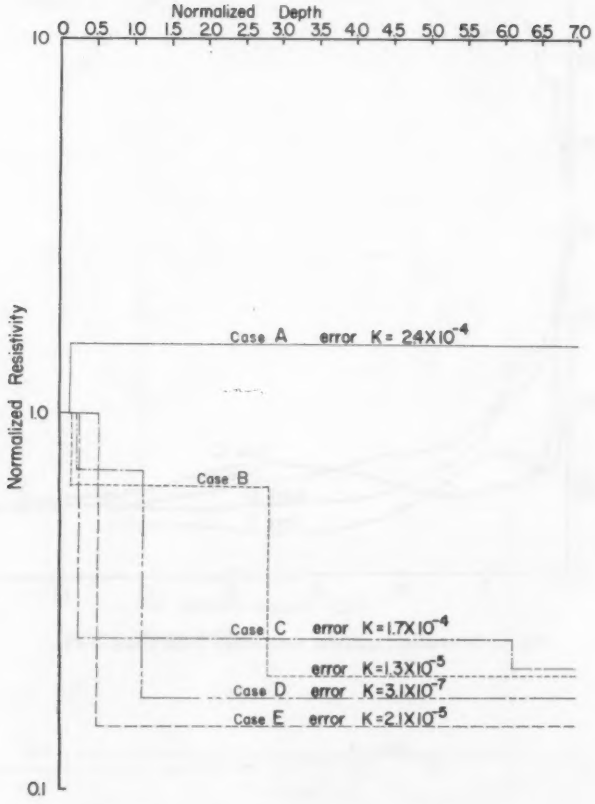


FIG. 13. Three-layer solutions (Field Cases A–E). (K is the sum of squares of errors in least square fit at 10 points.)

plete the evaluation of the numerical method, a comparison should be made with the results from curve comparisons. However, it is very unlikely that a sufficiently general set of curves will ever appear.

In analyzing Induced Polarization results, resistivity curves for each frequency must, of course, be treated separately and Metal Factors

$$\left(\frac{\rho_{\omega_1} - \rho_{\omega_2}}{\rho_{\omega_1}\rho_{\omega_2}} \times 10^5\right)$$

calculated for each layer.

APPENDIX

Calculation of M, Equation 7

The coefficient M is first estimated by approximating the ratio of first to second derivatives of K along the path defined by ∇K, i.e.,

$$M' = \frac{K_s}{K_{ss}} = \frac{\sum_i \frac{\partial K}{\partial \xi_i}\frac{d\xi_i}{ds}}{\sum_i \frac{\partial^2 K}{\partial \xi_i^2}\left(\frac{d\xi_i}{ds}\right)} . \tag{9}$$

Trial values of K are then calculated using c_1M' and c_2M' in equation 7

$$K(p_a^{(h+1)}) = K\left(p_a^{(h)} - M\frac{\partial K}{\partial p_a}\Big/ |\operatorname{grad} K|\right) \tag{7}$$

where c_1 and c_2 are unequal numbers near unity. The two values of K thus obtained, and the previous value of $K(p_a^{(h)})$ (corresponding to M multiplied by zero) can be used to interpolate for a value of M. Two kinds of interpolation were used, depending on the proximity to the minimum. If the two trial values of K are θ_1 and θ_2, a linear interpolation to $\theta=0$ is used when $|\theta_1-\theta_2| < K(p_a^{(h)})$, and a parabolic interpolation to $\theta=$ minimum is used when $|\theta_1-\theta_2| \geq K(p_a^{(h)})$. That is, at the beginning of the iterations, $K(p_a^{(h)})$ is quite large, and $|\theta_1-\theta_2| < K(p_a^{(h)})$. In this case it is assumed

$$\theta_1 = c_1\alpha + \beta$$
$$\theta_2 = c_2\alpha + \beta$$

and the equations are solved for the value of c which gives $\theta=0$. This is

$$c = -\frac{\theta_1 - \theta_2}{c_1 - c_2} .$$

When approaching the solution, a point is reached at which $|\theta_1-\theta_2| \geq K(p_a^{(h)})$ and from there on a second order interpolation is used. Assuming

$$\theta_1 = c_1^2\alpha + c_1\beta + \gamma$$
$$\theta_2 = c_2^2\alpha + c_2\beta + \gamma$$
$$\theta_3 = K(p_a^{(h)}) = \gamma \qquad (c_3 = 0)$$

and minimizing θ,

$$c = \frac{c_1^2(\theta_2 - \theta_3) + c_2^2(\theta_3 - \theta_1)}{\theta_1 c_1 - \theta_2 c_2 + \theta_3(c_1 - c_2)} .$$

In the analyses done numerically, c is generally in the range .5 to 1.5.

The iteration then proceeds using $M = cM'$.

Because of the flexibility of the procedure, computation time could probably be saved by using the Newton estimate

$$K' = \frac{K}{Ks}$$

in place of equation 9.

REFERENCES

Compagne Générale de Géophysique, 1955, Abaques de sondages électriques: Geophysical Prospecting, v. 3, supplement 3.

Hildebrand, F. B., 1949, Advanced calculus for engineers: New York, Prentice-Hall, Inc.

Householder, A. S., 1953, Principles of numerical analysis: New York, McGraw-Hill Book Company, Inc.

Langer, R. E., 1933, An inverse problem in differential equations: Bull. Amer. Math. Soc., Series 2, v. 29, p. 814–820.

———, 1936, On the determination of earth conductivity from observed surface potentials: Bull. Amer. Math. Soc., Series 2, v. 42, p. 747–754.

Mooney, H. M., and Wetzel, W. W., 1956, The potentials about a point electrode and apparent resistivity curves: Minneapolis, University of Minnesota Press.

Pekeris, C. L., 1940, Direct method of interpretation in resistivity prospecting: Geophysics, v. 5, p. 31–42.

von Sanden, H., 1923, Practical mathematical analysis: London, Methuen.

Slichter, L. B., 1933, Interpretation of resistivity prospecting for horizontal structure: Physics, v. 4, p. 307–322; also erratum, p. 407.

Stevenson, A. F., 1934, On the theoretical determination of earth resistance from surface potential measurements: Physics, v. 5, p. 114–124.

Sunde, E. O., 1949, Earth conduction effects in transmission systems: New York, D. van Nostrand.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 557–573, 13 FIGS.

SOME TECHNICAL ASPECTS OF REFLECTION SEISMIC PROSPECTING IN THE SAHARA*

M. PIEUCHOT† AND H. RICHARD†

ABSTRACT

The small signal-to-noise ratio encountered in the Sahara required the development of special techniques. The gentle dips and low frequencies permitted the use of a pattern of 100 shot holes recorded by an array of 100 or more geophones per trace with the linear dimensions of the arrays of the order of 100 m. The large structural dimensions allowed the compositing of as many as 5 records into a single trace. Seismic reflection exploration was made economically feasible by the use of pneumatic hammers for drilling and the less expensive nitrates for explosives. The experimental procedures leading to the selection of the techniques are described.

INTRODUCTION

The first attempts to use the seismic reflection method for exploration in the Sahara disclosed the presence of many factors unfavorable to the successful utilization of the usual seismic techniques. The water table is not always well defined, and it is sometimes very deep. It is difficult to drill shot holes through the surface formations which vary from hard and abrasive limestones and variable caliche to sand dunes. Below the surface limestone or caliche, there are thick sandy series which frequently rest upon more compact formations. Such a succession of formations tends to attenuate the signal transmission and to develop noise. Except in some favorable areas of small extent, the signal-to-noise ratio is small, and the first attempts made with deep shots to depths of 100 m and more were not successful.

By 1953 it was known that, for technical and economic reasons, deep shots were impractical, and the only type of procedure to investigate was a systematic use of a large number of geophones and shots, the latter being fired at shallow depth.

The problem became resolved into (1) a search for a combination of techniques that would yield usable data and (2) the reduction of these techniques to an economically feasible program by selecting suitable drilling techniques and the most efficient explosive. This paper attempts to give a description of the solution of these problems. So that this description may be fairly complete, it has been necessary to include some data and figures that have been published previously (Richard and Pieuchot, 1956; Richard, 1957; Pommier and Richard, 1957).

THE SPREAD

The search for a satisfactory shooting technique required the selection of the parameters of spread of multiple geophones and shots (up to 100 shots with

* Presented at the 27th Annual Meeting of the Society of Exploration Geophysicists at Dallas on November 12, 1957. Manuscript received by the Editor December 16, 1957.

† Compagnie Générale de Géophysique, Paris, France.

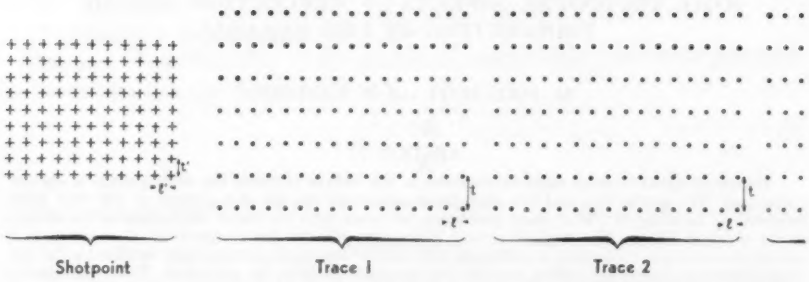


FIG. 1. Type of pattern used in the Sahara utilizing 99 shot holes in combination with 112 geophones per trace. The linear dimensions of the arrays were of the order of 100 m.

still more geophones per trace) and correct filter settings. It was also necessary to adapt the techniques to the size of the geological features.

Experience has shown that it was easier to set the geophones according to a pattern of lines parallel to the profile as shown in Figure 1. It offers these main advantages:

a. For a given area a high multiplication factor may be attained. The limitations to the size of the area will be discussed later.
b. It is possible to organize a fast and efficient planting operation when the geophones of adjacent traces make continuous lines as shown (Figure 1).
c. As far as noise cancellation is concerned, this pattern has more advantages than a one-line arrangement.
d. Determining the optimum distance between explosions or geophones is easy as the number of parameters is reduced to:
   l = longitudinal distance between consecutive geophones
   t = transverse distance between lines of geophones
   l' = longitudinal distance between explosions
   t' = transverse distance between lines of explosions.

The influence of these 4 parameters has been carefully studied so as to obtain the best out of a given number of geophones and explosions.

Number and Spacing of Geophones Per Trace

The first tests were limited to comparing results given by one line of 12 or 18 geophones with a spacing l of 5 to 10 m. With $l = 10$ m the noise level is 1.3 to 1.4 smaller than with $l = 5$ m. This first result led to using lines of 12 or 18 geophones covering a total length of 110 or 170 m.

Parallel lines with $l = 10$ m on each were connected together and their spacing t was set at 5, 10, and 20 m. Using 10 instead of 5 m, the noise was considerably reduced. With 20 m instead of 10, the reduction was much smaller but still noticeable except in a few instances.

The decision was reached that it was advantageous to choose a longitudinal spacing l of at least 10 m and a lateral spacing t of at least 20 m. Then the noise level was approximately determined by $0.8\sqrt{n}$, n being the number of geophones per trace. The spreads have been selected so as to make n as large as possible.

As will be discussed later, in some areas poor records have been interpreted by compositing all the traces of each record after making the necessary static and dynamic corrections.

Number and Spacing of the Shot Holes

The problem of the shotpoint pattern is still more important than the problem of the geophone pattern because it is easier and less expensive to use several scores or hundreds of geophones than the same number of buried shots even when the shot hole depths are small. There is justification, therefore, for making numerous experiments in order to evaluate the attenuation of noise with the variations of the shotpoint pattern to determine accurately the most economical spacing.

For a given shooting depth and charge, the noise level and its attenuation require measurement against variable hole-spacing. For the experimentation, the noise was generated in a geophone by the simultaneous shot of 8 charges placed, either on a longitudinal line or on a transverse one, with distances l' or t' of 0, 4, 8, and 16 m. Noise was recorded on a 12-trace spread with one geophone per trace. Under such conditions, reflected signals were negligible when compared with the noise.

Noise measurements with 8 charges as shown on Figure 2 were made in 3 different locations totaling 300 shot holes. Statistics derived from the results are shown on Figure 3 where

A are the noise levels of 32 single shots after multiplication by 8. This was assumed to correspond to the noise developed by 8 charges with zero spacing,
B are 8 results corresponding to a 4 m spacing,
C are 12 results corresponding to a 8 m spacing,
D are 12 results corresponding to a 16 m spacing.

The most probable relative values can be derived from the results. The curve of noise as a function of the spacing would be somewhere in the shadow zone on Figure 4. Shooting 8 charges simultaneously located on a longitudinal or transverse spread decreases by a 2.6 factor the noise level, provided their spacing is large enough. There is an advantage in putting them 10 meters or more apart.

The conclusion of these tests, which were made, let us remember, with some 300 experimental shot points, was that the spacing should not be smaller than 10 m. Then the noise level is divided by $K\sqrt{p}$ in which:

p is the number of individual shots
K is a constant slightly smaller than one.

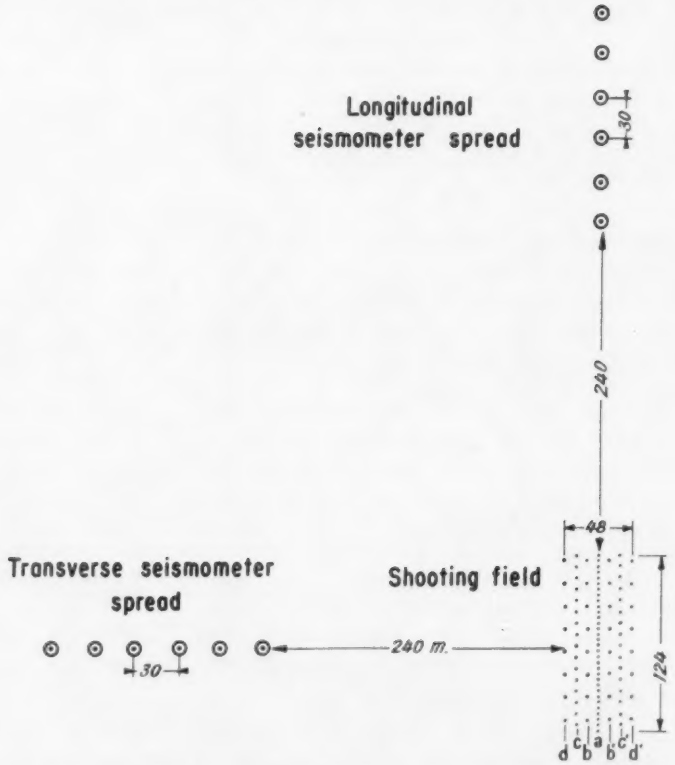


FIG. 2. Method of making noise tests. Noise level was measured on single geophones from shot hole arrays whose spacings were 0, 4, 8, and 16 m.

Among the shooting patterns that have been used, let us mention: (a) 7 lines of 10 holes with a 10 m spacing between holes of a line and 20 m between lines, and (b) 10 lines of 10 holes uniformly scattered in a 90 m by 90 m square.

Figure 5 shows the type of record so obtained with a high multiplication of shots and geophones. It is quite good, though no mixing whatsoever (spread or equipment) was used.

The high multiplication with shallow shots has been widely applied in the Sahara, and it allowed the obtaining of good quality cross-sections such as that shown in Figure 6. In a desert, it is easy to spread out the geophones. Furthermore, the dips are very gentle and the distance between adjacent traces can reach 100 m or more. Two difficulties arise, however, one from surface corrections and the other from well-known consequences of multiplication.

Surface Corrections

Without deeper holes and vertical time measurements, it is hard to get accurate corrections. The difficulty can be reduced with the following procedure.

a. Shallow continuous reflecting horizons are recorded and used as a reference. They are almost horizontal as a rule.
b. Velocity determinations using a statistical computation of the moveout are accurate enough to check velocity variations in the overburden above this reference reflection.
c. When an area is surveyed, some drill holes properly located can be used for a check.

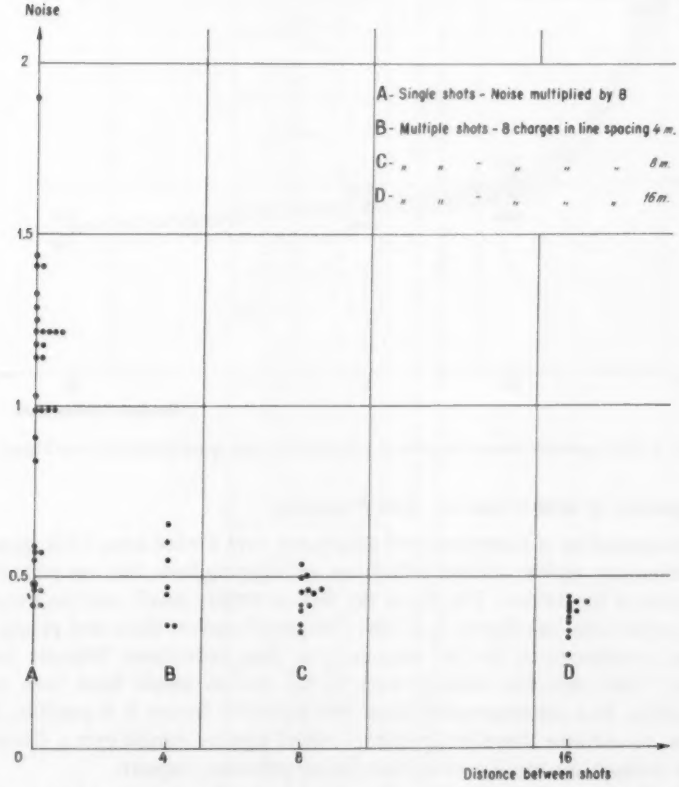


FIG. 3. Noise level as a function of shot spacing in meters is determined from three locations similar to the arrangement shown in Figure 2. The total energy recorded by a single geophone was assumed to be essentially noise. Responses were corrected to a standard of 8 unit charges.

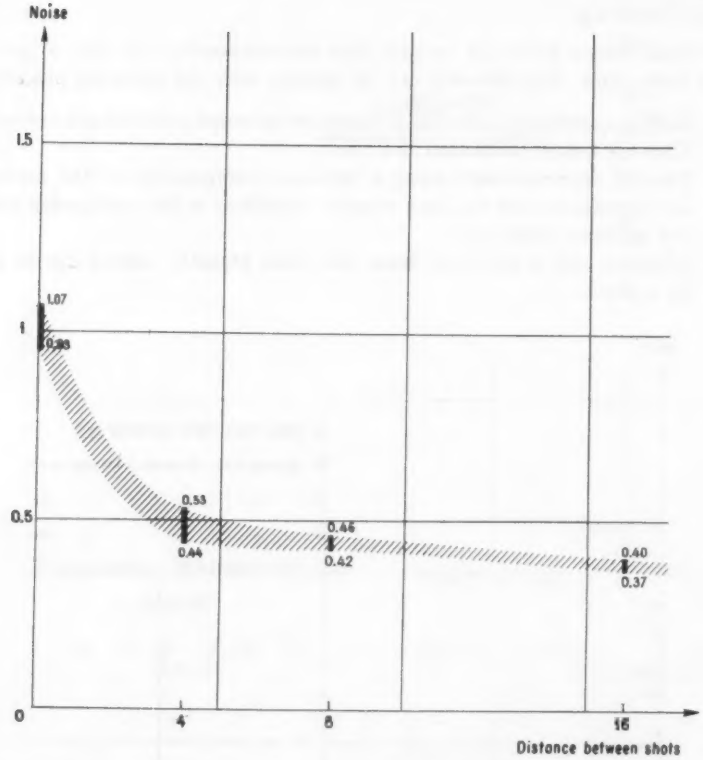


FIG. 4. Most probable values for noise as a function of shot spacing derived from Figure 3.

Consequences of Multiplication—Low Frequency

The spreading of interconnected geophones over a wide area, while generally discriminatory against shallow reflections and dipping beds, has less serious consequences in the Sahara. The dip of the beds is usually small, and the frequency of the reflections (see Figure 5) is low. The use of shallow shots and proper filter setting contributes to the low frequency of these reflections. Without low-frequency filters reflection seismic work in the Sahara would have been almost impossible. As a consequence of these two favorable factors it is possible, in the Sahara, to combine these low frequency, small dipping signals over a distance of 100 m without too much attenuation due to reflection stepout.

Weathering variations within the area covered by one trace, however, may disturb and even destroy the quality of a record. With present-day magnetic recording it becomes possible to overcome this difficulty by the use of more

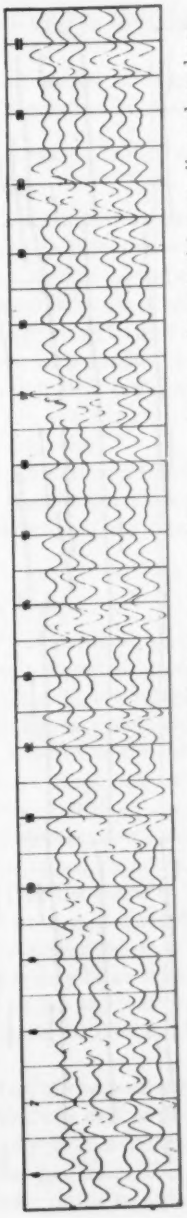


FIG. 5. An example of a seismogram obtained from an array similar to Figure 1 whose parameters were determined from studies such as shown in Figure 4. The small number of traces is a permissible economy because of the record quality obtained by these techniques.

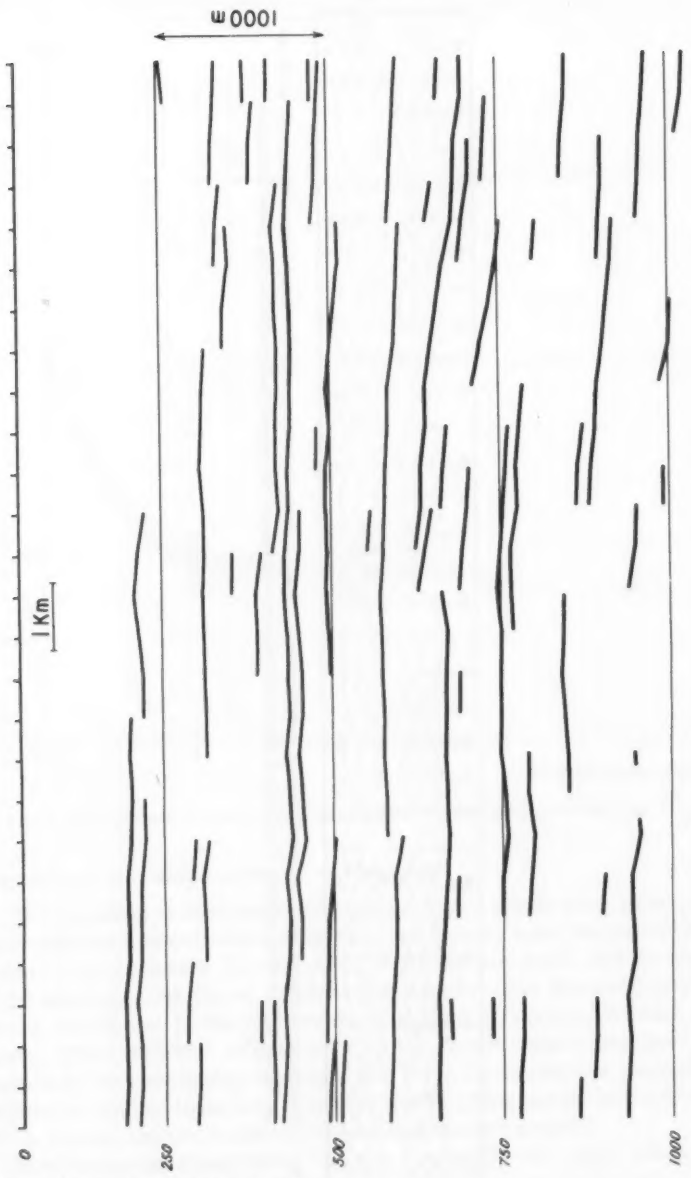


FIG. 6. A cross-section of 15 km illustrating the type of data obtainable by the use of 100 charges per shot and 108 seismometers per trace.

traces of less extension which may be composited only after correction for elevation and weathering effects.

Let us mention that we always avoided spread mixing. Each trace was absolutely independent, and this resulted in more reliable correlations.

MODE OF PRESENTATION OF THE RESULTS

Size of the Geological Features

The dimensions of the area of this survey are large. The distance from the northeast (Ouled Djellal) to the Paleozoic outcrops (In Salah) is 880 km, while from the northwest (Colomb Bechar) to the eastern border (Edjelé) is 1,330 km.

These distances cover what we might call a northern area where continental Quaternary and Tertiary cover up an important Mesozoic section. The structures are very extensive and show dips smaller than two to three degrees. The first reconnaissance work was conducted with long profiles of 100 km or more. The network then was reduced to a spacing of 10 to 25 km. Detail is worked out with loops having 2 to 5 km on each side.

In the South, Paleozoic formations generally outcrop. Structures are smaller; and dips, though greater, remain less than 10 degrees. The first profiles were shorter than those in the North, but the detail work is made with the same kind of network.

Mode of Presentation of the Results

The Sahara is a country of gentle dips and wide structures with several very continuous series. This has resulted in a constancy over long distances of the average shape of the reflections. Figure 7 depicts in 21 traces 60 km of continuous profiling. Each trace in this figure is obtained by a two-stage compositing. First, the recorded traces were corrected to the reference plane and mixed to obtain a composite corresponding to 72 geophones and a multiple shot of 24 charges. Five consecutive such composites were then corrected for dip along horizon S and mixed together. The three signals shown on the left of Figure 7 are third-stage composites of reflection S obtained by adding the 5 or 6 traces indicated by the brackets. It can be noted that the shape of the signal does not vary.

On the 21-trace record section, a disconformity appears below horizon S. It is so small that it might be unnoticed on a regular-scale cross-section. It is not meaningless, however, and it may be an important fact to consider in the Sahara.

Figure 7 was obtained by the algebraic addition of digitized data. Obviously, a similar record section would be obtainable by a suitably arranged magnetic playback.

The mode of presentation of the results has varied in time. At the beginning, the conventional time section was used with a wide scale: 1/5,000. The horizontal scale has been reduced gradually to 1/20,000, the better to show the very gentle slopes of a few milliseconds per mile. The next step is the "condensed record section." We apply this name to the record section in which each trace is a com-

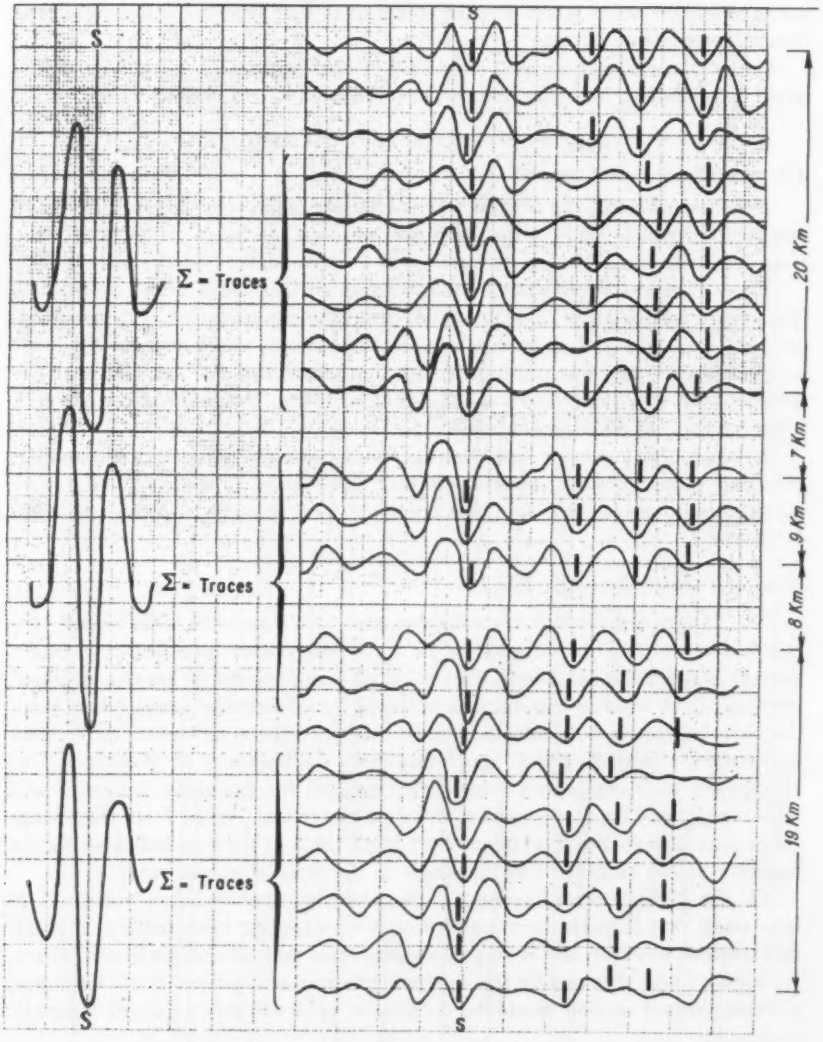


FIG. 7. A record section of 21 traces covering 63 km. Each trace is obtainable by adding 5 composites. Each composite corresponds to 24 shots recorded by 72 geophones. The three traces to the left show the further composition for 2.5 cycles of the S reflection of the respective bracketed traces. The indicated gaps in the data serve to show the correlation possibilities of these cumulative techniques.

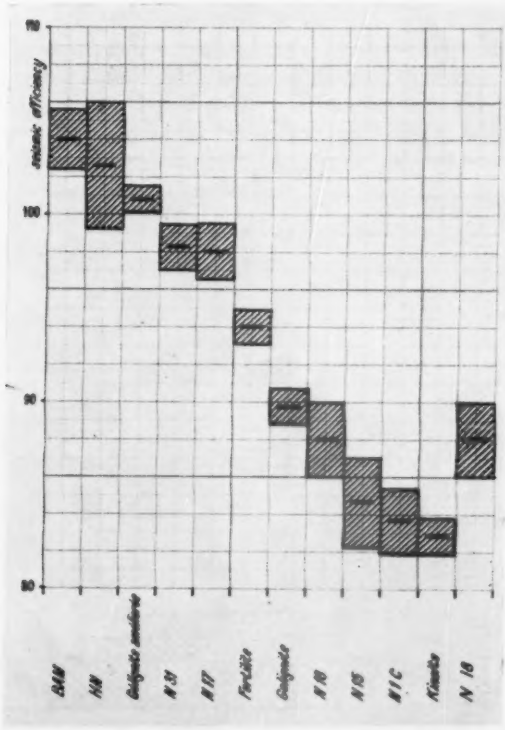


FIG. 8. A "coefficient of seismic efficiency" of various explosives. The dashes are the mean values measured. The shadow zones, related to the standard deviation, indicate the range of the most probable value. Data were obtained by recording 12.5 kg charges suspended two meters above the surface.

posite of several recorded traces, their number being limited by local conditions. Figure 7 is an extreme example of a condensed record section.

THE EXPLOSIVE

The surface formations are very absorbing of energy and the total charges must be large. They range from around 100 to 200 lb. The cost of transportation is, moreover, very high. The choice of a type of explosive is accordingly very important, and special experimentation was conducted in 1954 in the North of Sahara (Richard and Pieuchot, 1956). Many comparison shots were fired with eleven different types of explosives. A "coefficient of seismic efficiency" could be applied to each explosive by experimenting under regular seismic conditions instead of the laboratory tests from which the usual parameters (strength, velocity, etc.)

are derived. Figure 8 is an example of the results. The dash is the mean value measured and the shadow zone, related to the standard deviation, is that in which the true value has two chances out of three to stand. Figure 9 shows the cost of explosives for a constant seismic effect. The nitrates are the less expensive by far, and they have been extensively used in the Sahara. Their lack of water resistance and their low density are of no importance here, since they are to be

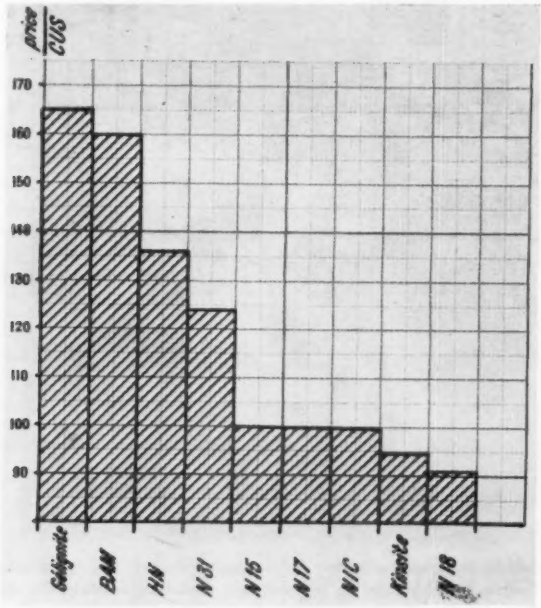


FIG. 9. The data of Figure 8 rearranged to show the cost of different explosives for the same seismic efficiency and indicating a range of nearly two to one.

used in dry holes. Their insensitivity to heat and shocks, furthermore, makes them quite safe. The use of nitrates instead of gelatine led to a considerable economy.

DRILLING

Drilling difficulties make it too expensive to shoot several deep holes at a time, and these techniques were thus discontinued. The difficulties are due to the nature of surface formations and to the lack of water. Sometimes the upper beds are hard and abrasive. Mud drilling was stopped very quickly because of the distance over which water had to be carried, and the drillers then turned to air drilling.

Failing drill model 1500 (Figure 10), equipped with a compressor, is still used for medium-depth shotpoints. Unfortunately, limestones with cherts wear out the rock bits very fast. Attempts to use shaped charges and spare the bits were

FIG. 10. Air drilling in the Sahara with a Failing unit. This type of unit was preferred where deeper holes were required.

not a success. Another type of drill, the Record HS, failed. This drill is used in quarrying, and it consists of a pneumatic hammer lowered into the hole. The cuttings are carried up by the exhaust air. The tool is economical, but the production was only three meters of hole per hour.

The Wagon-Jack is becoming more and more common in the Sahara. The seismologist is usually satisfied with shallow holes and a reduced diameter for small individual charges; but a conventional drill is too powerful for this work, and too much time is lost with bigger trucks. Pneumatic hammers are much more convenient, and two types of them have been tried, viz., a very light, jeep-mounted Warsop hammer and a Wagon-Jack on a GMC Truck.

The Warsop Jeep (Figure 11) is an automatic hammer energized by a two-

FIG. 11. Drilling with a Warsop jeep-mounted hammer. This unit is capable of drilling 10 to 20 holes per hour of depths of one or two meters.

cycle engine mounted in a framework at the back of the jeep. It weighs 40 kg, it uses a little more than ½-gallon of gasoline per hour, and it can drill an average of 10 to 20 holes of one to two meters per hour (travel time included) according

FIG. 12. Wagon-Jack. This unit can drill 20 to 30 holes per hour and is preferred for the drilling of shot hole arrays similar to the diagram of Figure 1.

FIG. 13. A Wagon-Jack unit drilling a multiple hole pattern in the Sahara.

to the hardness of the ground. The production is increased by adding a small compressor, driven by the jeep motor, for reinforcing the air draught.

The Wagon-Jack shown in Figure 12 can drill 20 to 30 shallow holes per hour according to the type of rock. The drilling crew (Figure 13) includes one driller, one helper-driver, and a shooter for loading the holes. The Wagon-Jack is quite satisfactory in the Sahara. Its advantages are:

—sturdiness
—big production
—low cost on bits
—easy and fast to move around.

CONCLUSION

Reflection seismic prospecting in the Sahara met difficulties which seemed prohibitive at first. Owing to technical improvements, however, it became possible to adapt procedures to the country and even to turn to one's advantage what looked like impediments. The low density of population allowed the use of very wide spreads. The lack of water led to a type of drilling and of explosive relatively cheap. It is noteworthy that such a wilderness is particularly suitable for trying new methods and new equipment and also for special experiments such as those about the seismic efficiency of explosives and concerning elastic anisotropy (Cholet and Richard, 1954). In the long run, the seismologist is repaid for his efforts, and the mile of profile in the desert is cheaper than in some other more attractive regions.

ACKNOWLEDGMENTS

We wish to express our thanks to the Compagnie Française des Pétroles en Algérie, to the Société Nationale de Recherche et d'Exploitation du Pétrole en Algérie, to the Compagnie Générale de Géophysique, and to Messrs. Jacques Cholet and Gilbert Pommier for permitting the field experimentation and for their cooperation in the work described in this paper.

REFERENCES

Cholet, Jacques, and Richard, Henri, 1954, A test on elastic anisotropy measurement at Berriane (North Sahara): Geophysical Prospecting, v. 2, p. 232–246.

Richard, Henri, and Pieuchot, Maurice, 1956, Seismic efficiency of explosives: Geophysical Prospecting, v. 4, p. 167–184.

Richard, Henri, 1957, Généralités sur la supermultiplication: Bulletin de l'Association Français des Techniciens du Pétrole, n. 122, p. 127–141.

Pommier, Gilbert, and Richard, Henri, 1957, Supermultiplication des charges et des sismographes au Sahara (Zone Nord): Geophysical Prospecting, v. 5, p. 282–299.

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 574–578, 5 FIGS.

CASE HISTORY OF THE SOJOURNER OIL FIELD HASKELL COUNTY, TEXAS, A GEOCHEMICAL CONFIRMATION*

W. R. RANSONE†

ABSTRACT

Petroleum accumulation at the Sojourner field, Haskell County, Texas, was found in a lower Pennsylvanian sand pinch out. The prospect was first recognized as anomalous on a reconnaissance geochemical survey, leased, and then detailed by reflections, on the basis of which the discovery well was located.

Since the field has been completely developed, the prediscovery predictions of the geochemical and reflection surveys can be compared with the subsurface known from well data. Pertinent maps are shown together with a discussion of the local geology and field development.

INTRODUCTION

The Sojourner field is located in Haskell County, Texas, three miles west and one mile south of the city of Haskell in gently rolling plains country. The reservoir is a typical stratigraphic trap with little or no associated folding.

HISTORY OF DEVELOPMENT

In 1945, the Crown Central Petroleum Company contracted with Geochemical Surveys of Dallas to survey, geochemically, the south half of Haskell County, Texas. At the time, there was no production in the area to be surveyed and subsurface information was available from scattered dry holes, none of which was within 4 miles of the subsequently discovered Sojourner oil field.

For their services Geochemical Surveys received cash plus an overriding royalty in any oil or gas discovered.

GEOCHEMICAL SURVEY

The sampling procedure, density, and contour level were the same as those described by the author (1948, p. 335–336). The results are shown on Figure 1, a portion of the original report map, made available through the courtesy of Mr. Ben Bloom of Crown Central Petroleum Corporation.

On the basis of the geochemical anomaly shown in Figure 1, the lease block, shown in Figure 2, was assembled and the prospect assigned the name "Rule."

REFLECTION SURVEY

On completion of this lease block, Crown Central employed a Hoard Exploration Company reflection crew to detail the prospect. The resulting reflection map is shown in Figure 3. Two "highs" are shown, one with four closed contours

* Paper read at the 27th Annual Meeting of the Society at Dallas on November 13, 1957. Manuscript received by the Editor January 13, 1958.

† Geochemical Surveys, Dallas, Texas.

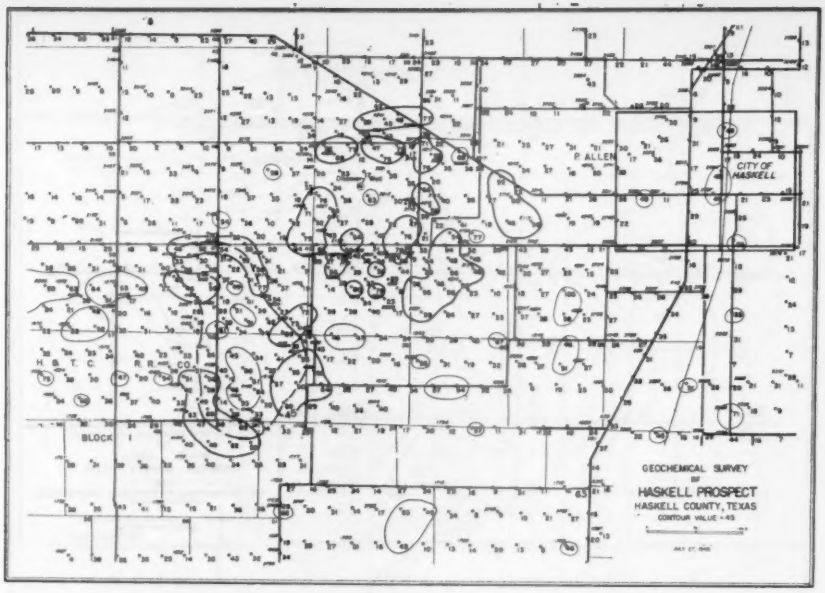


FIG. 1. A portion of the geochemical survey of Haskell County, Texas, conducted in 1946.

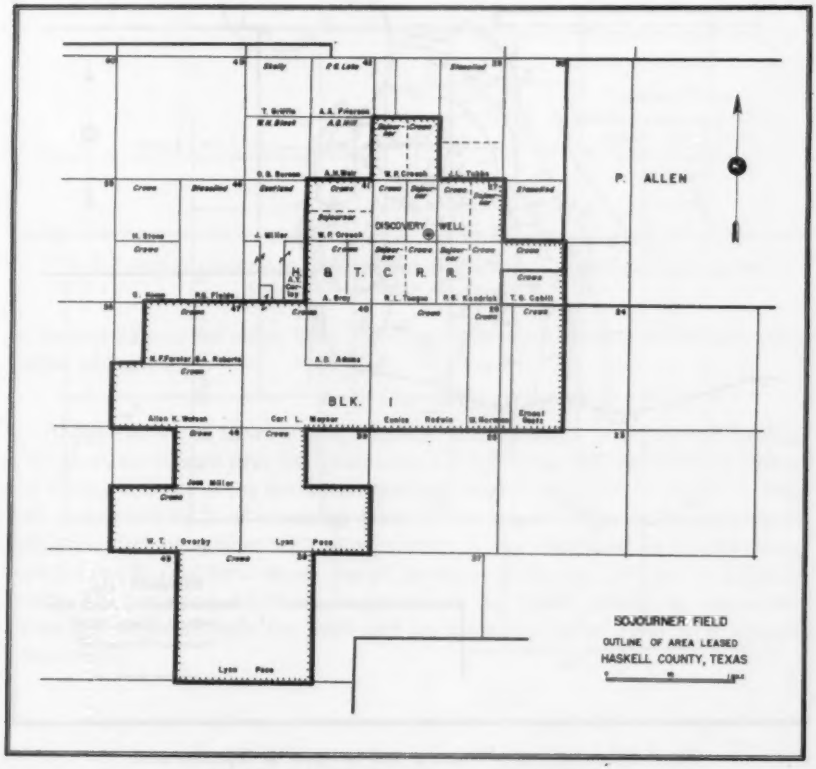


FIG. 2. Outline of area leased following geochemical survey.

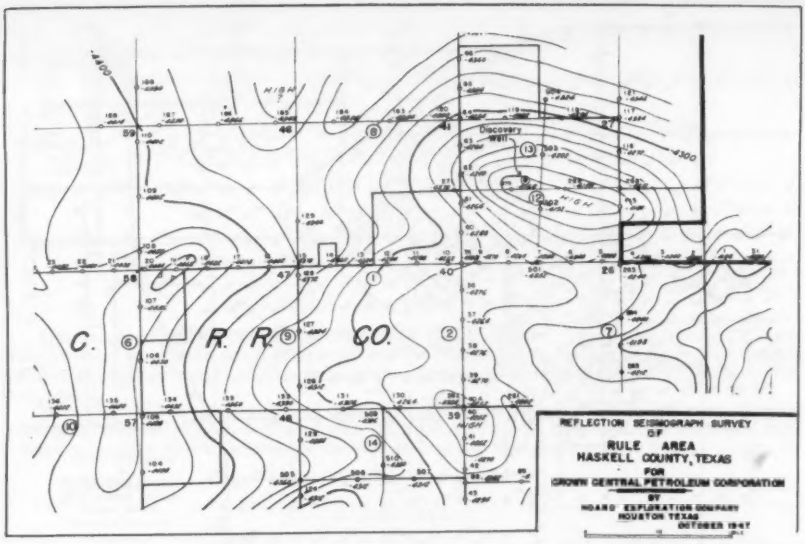


FIG. 3. Reflection seismic survey of Rule area. Contour interval is 20 ft.

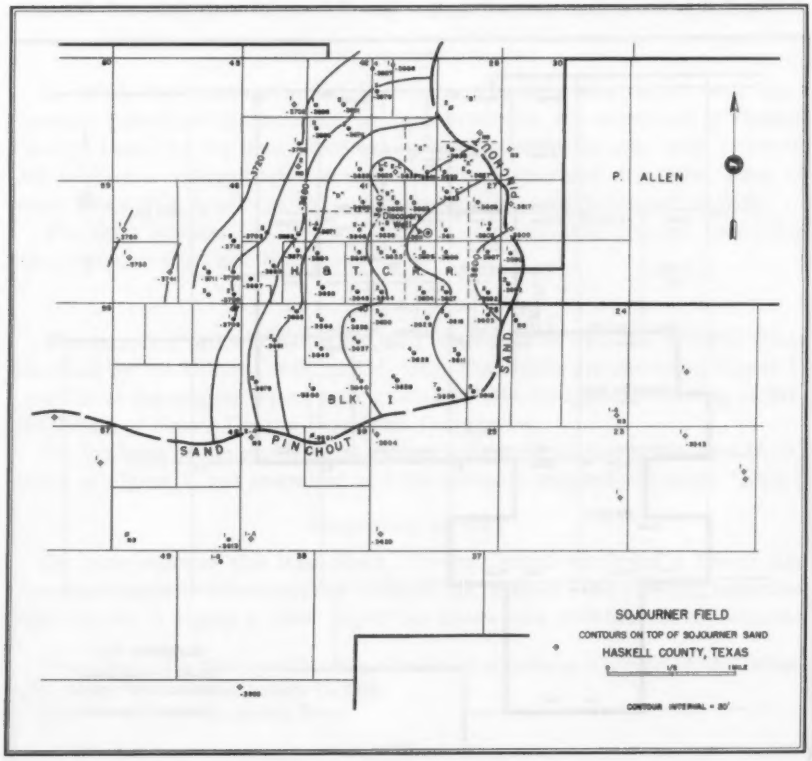


FIG. 4. Subsurface map of Sojourner field on top of the Sojourner sand. The contour interval is 20 ft as in Figure 3.

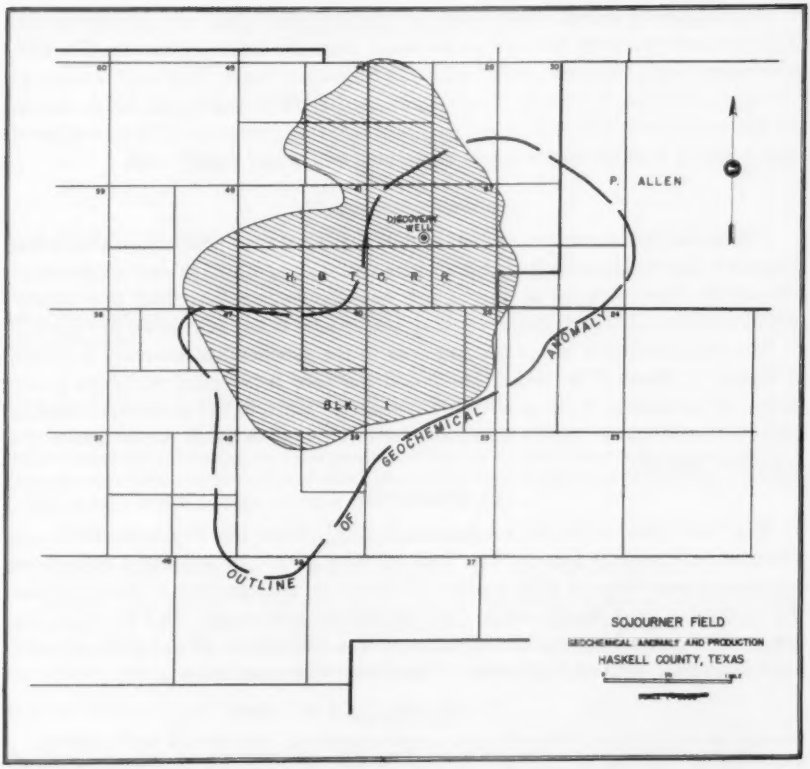


FIG. 5. Comparison between outline of geochemical anomaly as shown by dashed line and productive area shown by cross-hatching.

in Section 27 and the other, with one closed contour, centering at the northeast corner of Section 39.

DISCOVERY WELL

About two years later, Crown Central "farmed out," to Sojourner Drilling Company, an 80-acre drill site plus other acreage for a test well located within the closing contour of the northern reflection "high," as shown on Figure 3. This well penetrated 32 ft of saturated sand in the Strawn series of Pennsylvanian age, and, after being shot with nitroglycerin, it was completed as the discovery well (casing having been set on top of the pay), producing 250 bpd on a $\frac{1}{2}$-inch choke. The pay sand, which occurs just above the Caddo formation, was a new producing horizon; both the field and its main producing sand were named "Sojourner."

Possibilities of deeper production in the Sojourner field are considered unlikely because of a deep test drilled for water near the center of Section 27 which encountered no additional pays below the Sojourner sand. This well, known as the Sojourner Unit S-1 (R. L. Teague), located 1,080 ft south and 230 ft east of the discovery well, was drilled to a depth of 6,531 ft penetrating Cambrian sand from 6,380 to 6,460 ft where it was completed as a water supply well.

STRUCTURE

The subsurface structure, based on the fully developed field of some 70 wells, is a sand bar or lense with updip closure effected by a pinch out of the sand (Figure 4). The contours on top of the pay show some flattening but no closure at depths some 600 ft shallower than the reflection horizon shown in Figure 3.

The relationship of the producing area to the geochemical anomaly is shown in Figure 5. Most of the important producing area is included within or is adjacent to the outline of the geochemical anomaly. Much of the production outside and northwest of the geochemical anomaly is found in stray sands above the main pay horizon.

PRODUCTION

The total production as of August 1, 1957, from the Sojourner field now amounts to 3,200,000 barrels. The field has now been unitized and a pilot flood or pressure maintenance plan instituted. Water for repressuring is obtained from the Cambrian sand water source well previously mentioned. This is one of the few water floods which has been attempted in a field where all or nearly all wells have been shot with nitroglycerin or fractured with sand or both.

CONCLUSIONS

The Sojourner field, a stratigraphic trap, is a confirmation of the geochemical anomaly discovered on a regional reconnaissance survey in southern Haskell County, Texas. Adequate lease protection was afforded by the block taken on the basis of this geochemical anomaly.

The relief predicted by the reflection seismograph, if present, occurs about 600 ft below the depths explored to date by the drill.

REFERENCE

Ransone, W. R., 1948, Geochemical history of the Hardy oil field, Jones County, Texas: Geophysical Case Histories, Society of Exploration Geophysicists, v. 1, p. 334–341.

DEPARTMENTS

PATENTS

O. F. RITZMANN*

ELECTRICAL PROSPECTING

U. S. No. 2,819,447. W. C. Harmon. Iss. 1/7/58. App. 3/27/56. Assign. Republic Steel Corp.

System for Detecting Conductive Bodies. A tramp metal detector having a coil through which the material being tested passes connected in an oscillating circuit so that eddy currents in the metal affect the amplitude of oscillation but variations in the amount of non-conductive magnetic material are not detected.

GRAVIMETRIC PROSPECTING

U. S. No. 2,820,338. J. Rabinow. Iss. 1/21/58. App. 5/25/55.

Constant Periodic Motion Device. A precision clock whose pendulum swings inside another pendulum on colinear knife edges, the outer pendulum being made to keep pace with the inner one by a photoelectric system and servo-control which changes the distance of a magnet from the outer pendulum to make its rate coincide with that of the inner pendulum.

MAGNETIC PROSPECTING

U. S. No. 2,815,499. K. Brynes. Iss. 12/3/57. App. 2/23/56. Assign. General Electric Co.

Magnetic Field Detector. A flux-gate type of compass transmitter having an exciting winding surrounded by a thin, hollow, toroidal, high-permeability core material which is saturated by flux circulating around the minor circumference of the toroid, and having three polyphase windings on the toroid to pick up second harmonic induced by the ambient field in the plane of the toroid.

U. S. No. 2,822,515. J. M. Klaasse. Iss. 2/4/58. App. 7/13/55.

Spinning Type Magnetometer. A magnetometer having a flux-valve nutated about an axis and the output modulation filtered to obtain the vertical component and the horizontal component by phase comparison with signals from a directional gyro.

U. S. No. 2,823,545. P. K. Bodge. Iss. 2/18/58. App. 5/4/56. Assign. General Electric Co.

Magnetic Field Reactor and Systems Therfor. A flux-gate compass having an annular high-permeability core with position-phase windings and a central core with top and bottom radial arms of saturable magnetic material terminating above and below the annular core, the central core being wound with a d-c saturating winding and an a-c winding that induces signals in the position-phase windings.

RADIOACTIVITY PROSPECTING

U. S. No. 2,818,509. J. M. Johnston. Iss. 12/31/57. App. 9/2/53. Assign. U.S.A.

Radiac Survey Meter. A radioactivity detector circuit using an inverted vacuum tube with a floating plate circuit connected to the collector electrode of the ionization chamber.

U. S. No. 2,821,633. H. Friedman. Iss. 1/28/58. App. 6/30/55.

Scintillator. A radioactivity detector having a Vycor glass scintillator that scintillates in the visible spectrum region and a photomultiplier to detect the light.

* Gulf Oil Corporation, Patent Department.

U. S. No. 2,824,237. A. B. Witzel and F. E. Trainor. Iss. 2/18/58. App. 7/23/54. Assign. Admiral Corp.

Gaseous Discharge Tube Detector Circuits. A portable radioactivity detector for high intensity radiation in which the detector tube is pulsed so that the radiation is statistically sampled and the output pulses are integrated and indicated.

U. S. No. 2,824,971. I. F. Weeks. Iss. 2/25/58. App. 5/16/55. Assign. U.S.A.

Neutron Detector. A neutron detector having a gas chamber enclosing or containing a substance with good neutron absorption and measuring the pressure increase due to rise in temperature of the gas.

U. S. No. 2,824,973. J. C. Gundlach and G. G. Kelley. Iss. 2/25/58. App. 2/11/54. Assign. U.S.A.

Radiation Detector System. A portable radioactivity detector having a Geiger-Mueller tube to which power is supplied by a battery-operated multivibrator, the G-M tube being capacity coupled to a pulse amplifier.

U. S. No. 2,824,974. J. R. Parsons. Iss. 2/25/58. App. 8/14/53. Assign. U.S.A.

Radiation Detector. A portable radioactivity detector having a scintillating material and a photomultiplier whose output is fed to a voltage discriminator and pulses exceeding the threshold trigger a multivibrator and counter.

SEISMIC PROSPECTING

U. S. No. 2,814,991. J. C. R. Cance. Iss. 12/3/57. App. 5/21/52 and 4/30/53. Assign. Imperial Chemical Industries Ltd.

Art of Delay Electric Shot-Firing of Blasting Explosive Charges and Appliances Suitable for Use in Delay Electric Shot-Firing Circuits. A system for firing successive shots at short delay intervals in which each detonator except the first is in series with the contacts of an explosively-actuated switch which fires with the preceding shot.

U. S. No. 2,816,002. F. Baranowski, Jr. and J. L. Paine. Iss. 12/10/57. App. 6/1/54. Assign. General Electric Co.

Oscillograph Timing Line Mechanism. A timing line shutter mechanism having a slotted drum on a slotted shaft, the time scale being changed by either holding the shaft stationary or clamping the shaft to the drum.

U. S. No. 2,816,618. R. G. Piety. Iss. 12/17/57. App. 1/17/55. Assign. Phillips Petroleum Co.

Seismic Wave Generation by the Weight-Dropping Technique. A method of improving the useful seismic energy obtained by dropping a weight in which the impact area is saturated with water to a depth of several feet.

U. S. No. 2,816,748. F. B. Woestemeyer. Iss. 12/17/57. App. 12/30/54. Assign. General Electric Co.

Acceleration Responsive Device Having Limited Response. An accelerometer having a torsional spring-and-mass system suspended on the moving system to damp out accelerations of a predetermined unwanted frequency.

U. S. No. 2,817,905. B. E. Richert. Iss. 12/31/58. App. 8/5/54. Assign. Sun Oil Co.

Seismic Data Plotter. A geometrical device for plotting seismic reflections from observed travel times and taking into account a linear variation of velocity with depth.

U. S. No. 2,818,020. G. A. Burklund. Iss. 12/31/57. App. 11/17/55.

Safeguarded Electric Firing Initiating Devices. An electric blasting cap containing a condenser connected in parallel with the bridge wire to short circuit accidentally induced high-frequency energy.

U. S. No. 2,820,158. A. Mason. Iss. 1/14/58. App. 8/21/53. Assign. Bendix Aviation Corp.

Accelerometer. An accelerometer in which a non-uniform motion of a short-circuited coil in the air gap of a magnetic bridge induces a voltage unbalance in coils wound on the arms of the bridge.

U. S. No. 2,820,214. J. P. O'Neill. Iss. 1/14/58. App. 5/28/49. Assign. U.S.A.

Sonar Transducers. An underwater transducer having a cylindrical active area which is surrounded by a baffle made up of adjustable sound-attenuating slats to control the directional sensitivity pattern.

U. S. No. 2,820,912. W. T. Harris. Iss. 1/21/58. App. 10/1/53. Assign. The Harris Transducer Corp.

Magnetoelastic Transducer. A transducer having a three-legged ferromagnetic core with a coil on the center leg and a short air gap in the center leg so that elastic deformation of the core results from current in the coil.

U. S. No. 2,821,139. M. Apstein and A. O. Morse. Iss. 1/28/58. App. 10/9/56. Assign. U.S.A.

Shielded Initiator. An electric explosive initiator having a metal shell and a central lead wire with the bridge wire connected between the lead wire and the shell, the lead wire being surrounded with a lossy magnetic material to attenuate high frequency stray current.

U. S. No. 2,821,681. J. C. Baker. Iss. 1/28/58. App. 5/27/54 and 5/26/55. Assign. The Fairey Aviation Co. Ltd.

Resistance Meters. A blasting-cap circuit tester having a Wheatstone bridge energized from a photovoltaic cell excited by light from a battery-operated lamp.

U. S. No. 2,821,892. E. Merten. Iss. 2/4/58. App. 9/30/52. Assign. Shell Development Co.

Photographic Printing Apparatus for Seismic and Other Records. A photographic copying device for seismogram sheet having a graph of weathering in which the reproduction of each trace is manually shifted by keeping a sighting device on the weathering graph, a second reproduction being made by scanning at right angles and manually shifting the reproduction at depth by keeping a sighting device on a time-depth graph.

U. S. No. 2,823,606. D. P. Schafer. Iss. 2/18/58. App. 4/1/55. Assign. Willis L. Looney.

Seismogram Timing Lines Numbering Apparatus. A device for imprinting numbers on seismograms having hinged arms that carry an adjustable printing bar whose zero is set on the recorded shot moment, the bar being pressed against the seismogram through carbon paper to transfer the numbers to the seismogram.

U. S. No. 2,823,609. N. G. Johnson, G. A. Noddin and M. E. Swanson. Iss. 2/18/58. App. 4/15/53 and 5/24/56. Assign. E. I. Du Pont de Nemours and Co.

Device for Seismic Prospecting. A connector for insertion in a detonating fuse to introduce a time delay having in succession an enclosed explosive printing charge, an exothermic non-explosive mixture, an empty lead tube and an enclosed heat-sensitive detonating explosive.

U. S. No. 2,823,610. H. J. Frazer. Iss. 2/18/58. App. 1/23/56. Assign. Olin Mathieson Chemical Corp.

Blasting Cap Packages. A package for electric caps in which the cap is in a tube about which the lead wires are wound, the ends of the wires being held in a J-slot at the end of the tube.

U. S. No. 2,824,179. A. E. Tilley. Iss. 2/18/58. App. 6/16/54. Assign. California Research Corp.

Apparatus for Amplifying Seismic Signals. A seismograph avc system in which a pulse generated at the shot moment charges R-C circuits with controllable delay time, and a delayed pulse is used

to cut off the plate voltage from the avc amplifier to make the avc inoperative after the strong seismic impulses have passed.

U. S. No. 2,824,243. H. I. Sargeant. Iss. 2/18/58. App. 6/1/56. Assign. Hughes Aircraft Co.

Compression Type Accelerometer. An accelerometer having a piezoelectric wafer supporting a mass which contains a preamplifier tube connected to the wafer.

U. S. No. 2,824,483. C. H. Johansson. Iss. 2/25/58. App. 3/13/50 and 3/10/51. Assign. Nitroglycerin Aktiebolaget.

Device for Packing Explosive Cartridges into Bore-Holes. A shot-hole loading device having a tube through which the cartridges are lowered into the hole, the tube having knives at its inside lower end to cut open the cartridge wrapper as the cartridges are forced out of the bottom of the tube by means of compressed air injected at the top of the tube.

U. S. No. 2,825,039. G. A. Schurman and P. M. Aagaard. Iss. 2/25/58. App. 3/24/54. Assign. California Research Corp.

Connector for Detector Cable. A connector for interconnecting sections of a multi-conductor cable, the two halves of the connector being semi-cylindrical with their flat faces parallel to the cable axis and carrying plugs and sockets perpendicular to the cable axis.

WELL LOGGING

U. S. No. 2,815,577. M. C. Ferre. Iss. 12/10/57. App. 7/30/56. Assign. Schlumberger Well Surveying Corp.

Cable Measurements. A cable measuring device in which the cable passes in succession over two sheaves of different radii whose rotation is combined by a differential gear to eliminate errors of measurement caused by variations in cable diameter.

U. S. No. 2,815,578. D. E. Broussard. Iss. 12/10/57. App. 12/10/56. Assign. Shell Development Co.

Well Bore Calipering and Telemetering System. A caliper logging system in which the movement of several calipering arms is telemetered to the surface over a single-conductor cable by having a one-turn helical conductor in the sonde driven by a synchronous motor and having contactors whose axial positions are controlled by the respective caliper arms.

U. S. No. 2,815,969. M. P. Lebourg. Iss. 12/10/57. App. 5/19/54. Assign. Schlumberger Well Surveying Corp.

Lubricating Seal for Cables. A lubricator for running cable into a high-pressure well having a split gland which is assembled on the cable and inserted in a sleeve on the well head, the cable being lubricated by pressure fluid supplied from tanks through ducts in the two parts of the gland.

U. S. No. 2,816,235. S. A. Sherbatskoy. Iss. 12/10/57. App. 2/15/54. Assign. PGAC Development Co.

Radioactivity Well Logging Calibrating System. A method of calibrating a neutron-neutron logging apparatus by placing the sonde in a cylinder of phenolic resin and adjusting the response to a standard value.

U. S. No. 2,816,242. C. Goodman. Iss. 12/10/57. App. 5/19/53. Assign. Schlumberger Well Surveying Corp.

Neutron Sources. A neutron source having a central positive electrode with a number of needle-like points, an ionizable gas at low pressure, and a negatively-charged target surrounding the electrode, the target being of a material that gives off neutrons when bombarded with positive ions from a high-intensity field cold discharge.

U. S. No. 2,816,440. M. A. Garrison. Iss. 12/17/57. App. 1/10/55. Assign. Johnston Testers, Inc.

Tension Type Pressure Recorder. A bottom-hole pressure gauge having a diaphragm which separates well fluid from oil inside the gauge with the oil pressure acting on a rod and spring to actuate a recording stylus.

U. S. No. 2,819,038. J. E. Eckel. Iss. 1/7/58. App. 1/14/55. Assign. Esso Research and Engineering Co.

Reservoir Sampling. A bottom-hole sampler having an air hammer at the bottom of the drill string and a basket for catching cuttings.

U. S. No. 2,819,408. G. Swift. Iss. 1/7/58. App. 12/4/52. Assign. Well Surveys, Inc.

Instrument Zeroing for Radioactivity Well Logging. A system for recording the zero line in a radioactivity logging apparatus by temporarily applying a voltage to the detector that provides zero net ion-collecting field, the zeroing voltage being applied and removed by a latching relay that responds to a pulse signal from the surface.

U. S. No. 2,819,537. E. G. Peebles. Iss. 1/14/58. App. 4/30/54. Assign. ½ to Oscar O. Collins.

Drift Indicator. A well inclinometer which may be dropped down the drill string to a centering seat and having a shock-absorbing spring with a piston that brings the record blank into engagement with a pendulum.

U. S. No. 2,822,688. B. F. Wiley. Iss. 2/11/58. App. 1/24/55. Assign. Phillips Petroleum Co.

Flowmeter. A well flow meter having a packer and two flow paths from one side of the packer to the other, one path having a motor-driven impeller whose speed is controlled and indicated at the surface, and the second path having electrically-heated thermistors in a bridge circuit sensitive to the cooling effect of flow so that the impeller can be adjusted for zero flow in the second path.

U. S. No. 2,823,349. L. N. French. Iss. 2/11/58. App. 8/10/53. Assign. Phillips Petroleum Co.

Electrical Well Logging. An electric dip meter whose sonde has a long cylindrical electrode maintained centered in the well bore and having at its midsection electrodes connected to the same current source as the cylinder but insulated from it, the current to the cylinder and to each of the other electrodes being separately measured.

U. S. No. 2,824,233. G. Herzog. Iss. 2/18/58. App. 12/29/51. Assign. The Texas Co.

Controlling Scintillometer Temperature. A system for cooling a scintillation-type radioactivity detector in well logging by surrounding the cathode of the photomultiplier with a solid substance that melts during use in the well.

U. S. No. 2,824,236. G. Swift. Iss. 2/18/58. App. 5/10/54. Assign. Well Surveys, Inc.

Sensitivity Adjustment for Radioactivity Well Logging. A self-balancing servo controlled potentiometer for a well logging device in which the balancing voltage is obtained from a logarithmic potentiometer and the scale adjusted to coincide with the indication produced by a known standard.

U. S. No. 2,824,238. D. D. Stellmacher. Iss. 2/18/58. App. 10/3/55. Assign. Hoffman Electronics Corp.

Radiation Detection Pulse Translating Circuit. A pulse transmission circuit for radioactivity well logging in which the center electrode of a Geiger tube is connected through the primary winding of a transformer in the sonde to one cable conductor and the secondary of a transformer at the surface to a high voltage supply, and the secondary of the transformer in the sonde connected over the same cable conductor and a second cable conductor to the primary of the transformer at the surface.

U. S. No. 2,824,279. M. C. Ferre and A. H. E. Herrald. Iss. 2/18/58. App. 1/19/53. Assign. Schlumberger Well Surveying Corp.

Control Circuit for Electrical Logging Apparatus. An electric logging system in which auxiliary electrodes for focusing and monitoring are used, the principal electrode and the focusing electrodes being interconnected in the sonde by a control circuit having linear and non-linear elements in a bridge circuit so that zero potential between the monitoring electrodes automatically provides focusing current control without requiring additional cable conductors.

U. S. No. 2,824,380. N. A. Nelson. Iss 2/25/58. App. 7/1/54. Assign. Esso Research and Engineering Co.

Drill Hole Slope Indicator. An inclinometer having a pendulum whose lower end is clamped by a spring-operated piston with stepped recesses when mud pump pressure is removed, the particular step catching the pendulum being determined by the time required between the application of mud pressure and release of pressure by a valve when the piston returns a valve to an open position.

U. S. No. 2,825,044. G. Peterson. Iss. 2/25/58. App. 8/2/49.

Method of and Apparatus for Investigating Subterranean Strata. An acoustic logging system in which a pulsed beam of ultrasonic radiation is transmitted to the formation in a known azimuth and the time required for the reflected pulse to reach a receiver in the same azimuthal plane is measured to determine the profile of the formations.

MISCELLANEOUS

U. S. No. 2,816,257. D. L. Burdorf. Iss. 12/10/57. App. 8/27/56. Assign. Consolidated Electrodynamics Corp.

Speed Control Apparatus. A speed control system for a magnetic tape reproducer in which the main drive motor is coupled to the tape through a fluid clutch, and short period speed changes are corrected by a servomotor connected directly to the tape while long period speed changes are corrected by a servomotor which loads the main drive motor, the servos being controlled by a previously-recorded standard-frequency signal that is fed into a tuned discriminator.

U. S. No. 2,817,235. L. R. Hunter and L. P. Meade. Iss. 12/24/57. App. 3/22/54. Assign. Phillips Petroleum Co.

Temperature Measuring System for Underground Storage Cavern. An arrangement for measuring the temperature in a mined cavern having a number of sealed resistance thermometers at various points in the cavern with leads running down the shaft.

U. S. No. 2,817,707. E. S. Weibel. Iss. 12/24/57. App. 5/7/54. Assign. Bell Telephone Laboratories, Inc.

Synthesis of Complex Waves. A system of synthesizing complex (speech) waves by supplying oscillatory energy to two resonant circuits in parallel with a phase-inverter in series with one of the circuits and combining the outputs of the resonant circuits.

U. S. No. 2,818,503. F. M. Mayes. Iss. 12/31/57. App. 10/18/51. Assign. Sun Oil Co.

Elevation Meter. A vehicle-transported elevation-difference meter having a pendulum the sine of whose angle of inclination is integrated over the path by means of thyratrons in circuits which are unaffected by transients.

U. S. No. 2,819,476. R. J. Dodge. Iss. 1/14/58. App. 6/13/55. Assign. Buoys, Inc.

Floating Marker. A marine marker having an anchor fastened by a short chain to a mast that extends above the water surface and holds a marker vane, an adjustable float being clamped on the mast at a point just under the lowest water level encountered.

U. S. No. 2,820,610. J. D. Martinez. Iss. 1/21/58. App. 8/3/55. Assign. Esso Research and Engineering Co.

Multiple Magnetization Device for Well Cores. A core barrel having diametrically-opposed electromagnets which are controlled by a pressure switch so that whenever mud circulation is stopped the magnets are turned on to magnetically mark the core and a multi-shot surveying instrument simultaneously records the azimuthal orientation and inclination of the drill.

U. S. No. 2,820,961. M. Wallace. Iss. 1/21/58. App. 1/16/53. Assign. Panoramic Radio Products, Inc.

Navigational System. A system for reproducing the positions of separate aircraft in each aircraft of a group in which the radar distance-measuring equipment of each plane is actuated by the rotating phase of an omni-directional radio beacon so that each plane can receive and translate the position information of the other planes as well as its own.

U. S. No. 2,820,962. J. E. Hawkins and E. J. Crossland. Iss. 1/21/58. App. 4/23/54. Assign. Seismograph Service Corp.

Radio Location System. A phase-comparison radio-location system using coarse, medium, and fine position-determining systems, the coarse and fine systems using separate channels and the medium system using signals obtained by modulation with reference signals representative of the difference frequencies between the carriers.

U. S. No. 2,821,636. S. Jefferson. Iss. 1/28/58. App. 4/18/55. Assign. U.S.A.

Go-Devils. A container for a radioactive tag on a pipeline scraper, the radioactive source being carried in a piston held inside a thick shield by a spring and moved out of the shield by the pipeline pressure when in operation.

U. S. No. 2,821,680. M. L. Slusser, D. K. McLean, and H. A. Barclay. Iss. 1/28/58. App. 4/12/56. Assign. Socony Mobil Oil Co., Inc.

Apparatus for Use in Determining Characteristics of Porous Material. A core testing apparatus in which the core is enclosed in a flexible insulating sleeve with perforated metal inserts which serve as electrodes and pressure taps.

U. S. No. 2,824,689. J. S. Aronofsky. Iss. 2/25/58. App. 11/7/51. Assign. Socony Mobil Oil Co., Inc.

Electrolytic Analogue. An analog computer for solving Laplace's equation in cylindrical coordinates for a layered system having axial symmetry using a tank of electrolyte with a sloping bottom having sections of different slope to represent different parameters for different layers of the system.

SELECTED LIST OF U. S. PATENTS ISSUED DURING DECEMBER, 1957 AND JANUARY AND FEBRUARY OF 1958

Patent No.	*Subjects**	*Patent No.*	*Subjects**	*Patent No.*	*Subjects**
2,814,945	496	2,185,424	428	2,815,659	168
2,814,946	428	2,815,454	68	2,815,662	188
2,814,949	148	2,815,499[a]	232, 216	2,815,667	16
2,814,955	16	2,815,505	316	2,815,668	16
2,814,991[a]	136	2,815,577[a]	520	2,815,675	324
2,815,169	68	2,815,578[a]	44	2,815,913	68
2,815,216	484	2,815,584	16	2,815,969[a]	116, 304, 520

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947).

[a] Abstracted on preceding pages of this issue.

Patent No.	Subjects*
2,816,001	324
2,816,002[a]	368
2,816,056	484
2,816,174	224
2,816,175	224
2,816,176	224
2,816,232	196
2,816,235[a]	304
2,816,236	492
2,816,242[a]	308
2,816,250	68
2,816,257[a]	324, 224
2,816,440[a]	288
2,816,441	148
2,816,443	288
2,816,444	288
2,816,448	16
2,816,618[a]	360
2,816,619	484
2,816,722	16
2,816,723	16
2,816,748[a]	4
2,817,021	324
2,817,060	140
2,817,083	312
2,817,148	68
2,817,161	68
2,817,229	168
2,817,231	496
2,817,234	200
2,817,235[a]	452
2,817,239	16
2,817,240	16
2,817,477	68
2,817,478	68
2,817,479	68
2,817,707[a]	12
2,817,768	308
2,817,769	196
2,817,771	308
2,817,779	368
2,817,801	324
2,817,829	224
2,817,831	68
2,817,833	316
2,817,834	312
2,817,835	316
2,817,905[a]	352
2,817,906	444
2,817,974	16
2,817,975	16
2,818,020[a]	136
2,818,211	68
2,818,464	224
2,818,471	484
2,818,503[a]	444
2,818,507	236
2,818,508	196
2,818,509[a]	308
2,818,726	288
2,818,731	288
2,818,732	460
2,818,808	48
2,818,809	136
2,818,830	492
2,819,017	68
2,819,018	68
2,819,019	68
2,819,038[a]	36
2,819,052	4
2,819,053	4, 68
2,819,186	224
2,819,341	12
2,819,342	12
2,819,348	12
2,819,349	224
2,819,350	224
2,819,351	484
2,819,402	196
2,819,408[a]	304
2,819,437	148
2,819,447[a]	132
2,819,461	316
2,819,476[a]	360
2,819,537[a]	520, 192
2,819,605	412
2,819,610	496
2,819,613	140
2,819,614	188
2,819,615	288
2,819,673	48
2,819,771	12
2,819,940	224
2,820,107	484
2,820,158[a]	4
2,820,159	380
2,820,161	380
2,820,173	420
2,820,188	16
2,820,214[a]	484
2,820,219	316
2,820,303	16
2,820,338[a]	180
2,820,363	148
2,820,364	148
2,820,610[a]	84, 80
2,820,688	68, 224
2,820,840	460
2,820,871	68
2,820,895	308
2,820,896	308
2,820,898	316, 444
2,820,905	308
2,820,912[a]	484
2,820,937	68
2,820,947	500
2,820,956	224
2,820,961[a]	312
2,820,962[a]	312
2,820,963	316
Re.24,420	252
2,821,083	16
2,821,084	148
2,821,087	16
2,821,136	48
2,821,139[a]	136
2,821,462	168
2,821,575	224
2,821,576	224
2,821,583	16
2,821,633[a]	308
2,821,636[a]	308
2,821,680[a]	88
2,821,681[a]	136
2,821,694	108
2,821,695	16
2,821,701	316
2,821,704	312
2,821,791	16
2,821,792	68
2,821,855	288
2,821 857	412
2,821,859	16
2,821,892[a]	352
2,821,954	12
2,821,955	12
2,821,956	12
2,822,131	68
2,822,427	224
2,822,428	224
2,822,474	68
2,822,479	308
2,822,482	484

Patent No.	*Subjects**
2,822,511	68
2,822,515[a]	232
2,822,536	316
2,822,537	316
2,822,540	312
2,822,618	444
2,822,619	68
2,822,688[a]	148
2,822,689	288
2,822,694	16
2,822,695	16
2,822,977	68
2,822,978	68
2,822,979	68
2,822,981	68
2,823,346	188
2,823,349[a]	116
2,823,351	68
2,823,352	160
2,823,375	316
2,823,377	316
2,823,378	312
2,823,464	16
2,823,541	496
2,823,543	288
2,823,545[a]	216
2,823,577	416
2,823,606[a]	368
2,823,609[a]	360
2,823,610[a]	360, 136
2,823,855	68
2,823,856	68
2,823,857	68
2,823,877	16
2,823,974	108
2,824,178	484
2,824,179[a]	344, 372
2,824,233[a]	304
2,824,234	308
2,824,235	196
2,824,236[a]	304
2,824,237[a]	308
2,824,238[a]	308, 304
2,824,243[a]	4
2,824,252	308
2,824,278	200
2,824,279[a]	116
2,824,281	140
2,824,301	316
2,824,304	16, 444
2,824,380[a]	192, 520
2,824,387	436, 108
2,824,483[a]	360, 136
2,824,689[a]	68
2,824,690	68
2,824,692	68
2,824,693	68
2,824,694	68
2,824,776	224
2,824,789	168
2,824,906	12
2,824,968	416
2,824,971[a]	308
2,824,972	416
2,824,973[a]	308
2,824,974[a]	308
2,824,979	140
2,824,980	484
2,925,039[a]	360, 40
2,825,044[a]	8
2,825,053	316
2,825,055	68
2,825,056	316

REVIEWS

REVIEWS COMMITTEE

FRANKLYN K. LEVIN, Chairman, Jersey Production Research Company, Tulsa, Oklahoma
W. T. BORN, Geophysical Research Corporation, Tulsa, Oklahoma
THOMAS A. ELKINS, Gulf Research and Development Company, Pittsburgh, Pennsylvania
W. W. GARVIN, California Research Corporation, La Habra, California
SIGMUND I. HAMMER, Gulf Research and Development Company, Pittsburgh, Pennsylvania
CHWAN-CHANG LEE, Temco Aircraft Corporation, Dallas, Texas
JOHN E. NAFE, Lamont Geological Observatory, Palisades, New York
CARL H. SAVIT, Western Geophysical Company of America, Los Angeles, California
VICTOR VACQUIER, Scripps Institution of Oceanography, La Jolla, California
J. E. WHITE, The Ohio Oil Company, Littleton, Colorado

CONTENTS

General Theorems on the Equivalence of Group Velocity and Energy Transport, M. A. Biot, By *W. W. Garvin* 588
A Gravity Survey on Volcano Mihara, Ooshima Island, by Means of a Worden Gravimeter, Izumi Yokoyama and Hirokazu Tajima, By *Thomas A. Elkins* 589
Temperature Estimation of Pyroclastic Deposits by Natural Remanent Magnetism, Shigeo Aramaki and Syun-iti Akimoto, By *James Affleck* 589
Salt Water Encroachment of Ground Water in Northwestern Germany, Rudolf Wager, Wolfgang Richter, and Herbert Flathe, By *Victor Vacquier* 590
Selection of the Best Frequency in Using Inductive Methods of Electrical Exploration, F. M. Kamentskiy, A. A. Kaufman, and Yu. V. Yakubouskiy, By *James R. Wait* 590
Stockholm Natural Radiocarbon Measurements I, H. G. Ostlund, By *H. A. Shillibeer* 590
Structure of the German Alpine Foreland Molasse with the Aid of Seismic Velocities, Horst John, By *Carl H. Savit* 591
Exploring the Atmosphere's First Mile, Edited by Heinz H. Lettau and Ben Davidson, By *A. R. Kassander* 592

General Theorems on the Equivalence of Group Velocity and Energy Transport; M. A. Biot, *The Physical Review*, Vol. 105, 1957, pp. 1129–1137.

This paper shows that a rigorous identity exists between group velocity and velocity of energy transport under very general conditions. The medium is assumed to be non-dissipative, but it can be non-homogeneous provided its parameters are independent of the cartesian coordinate lying in the direction of mode propagation. The results of Brillouin[1] and Broer[2] are thus extended to non-homogeneous media (subject to the above geometric and physical limitation) for electromagnetic and elastic waves.

The method used to prove the identity consists of first deriving an expression for the group velocity using the concept of stationary phase and then showing that this expression is identical to the ratio of energy flux to energy density. This ratio is equal to the velocity of energy propagation.

An application of this identity has recently been suggested by Tolstoy.[3] The calculation of group velocity usually requires numerical differentiation of phase velocity with respect to frequency. The ratio of energy flux to energy density, however, can easily be computed, and it thus avoids the in-

[1] L. Brillouin, *Wave Propagation in Periodic Structures* (New York: Dover Publications, 1946).
[2] L. F. J. Broer, *Applied Science Research*, A2 (1951), 329.
[3] I. Tolstoy, *Journal of the Acoustical Society of America*, XXVIII (1956), 1182.

accuracies inherent in numerical differentiation. The results of the present paper prove the validity of this procedure in a wide variety of cases which are of interest to seismologists.

W. W. GARVIN
California Research Corporation
La Habra, California

A Gravity Survey on Volcano Mihara, Ooshima Island, by Means of a Worden Gravimeter, Izumi Yokoyama and Hirokazu Tajima, *Bulletin of the Earthquake Research Institute, University of Tokyo*, Vol. 35, Part 1, 1957, pp. 23–33.

Gravimeter surveys over volcanoes are still enough of a rarity to make a brief account of this paper worth-while. Another such gravimeter survey (26 stations) is described by Professor George Prior Woollard, "A gravity reconnaissance of the island of Oahu," *Transactions, American Geophysical Union*, Vol. XXXII (1951), pp. 358–368.

The present survey, made in August, 1956, using a Worden gravimeter, comprises 66 stations scattered over the entire island. In order to calculate the Bouguer correction it was necessary to estimate the density of the volcano mass. There appeared to be a linear relation between the observed gravity values and the elevations (Figure 2 of the paper); by least squares a density value of 2.08 g/cm³ was found; consequently 2.1 g/cm³ was used for the Bouguer correction to derive a contour map of the Bouguer anomaly (Figure 3 of the paper). For topographical corrections, densities of 2.1 g/cm³ and 1.03 g/cm³ were used for land and sea water respectively. In order to study the deeper structure of the volcano, that is, the approximate density distribution below sea level, a second Bouguer anomaly map (Figure 4 of the paper) was prepared in which a density of 2.4 g/cm³ was used for the Bouguer correction over eastern and northern portions of the island which were gravity high zones on the first Bouguer anomaly map. For the rest of the data in this case a density of 2.0 g/cm³ was used; both values were estimated by the same least squares method.

The Bouguer anomaly contours are roughly similar to the outline of the island. Detailed quantitative interpretation of the data is reserved for future studies.

THOMAS A. ELKINS
Gulf Research and Development Company
Pittsburgh, Pennsylvania

Temperature Estimation of Pyroclastic Deposits by Natural Remanent Magnetism, Shigeo Aramaki and Syun-iti Akimoto, *American Journal of Science*, Vol. 255, 1957, pp. 619–627.

This paper shows the results of measurements of remanent magnetizations in volcanic materials of different types. The basis of the study is that volcanic material deposited in its present location at a temperature higher than the Curie Point of the included ferromagnetic minerals should show a thermo-remanent magnetization in the direction of the earth's magnetic field. On the other hand, rock material deposited at lower than Curie Point temperatures should have random orientation of magnetization in the various rock samples. A check had to be made to show that the various magnetizations were stable and were not due to reorientations with time in the direction of the present earth's field.

Seven eruptions were studied. The temperature of the flows could be estimated from the condition of the rocks and inclusions such as wood. The magnetizations in each case conformed to the other evidence—that is, the low temperature flows showed random stable magnetization, while the high temperature flows showed a consistent magnetization direction.

This study suggests that these magnetic measurements may be useful as a technique in determining the temperatures of formation of volcanic deposits. It may have another significance, in my opinion. These workers, under Nagata, are doing an excellent job of advancing the knowledge of rock magnetism, and their experiments may lead to useful knowledge of the fundamental nature and sources of magnetic anomalies.

JAMES AFFLECK
Gulf Research and Development Company
Pittsburgh, Pennsylvania

Salt Water Encroachment of Ground Water in Northwestern Germany (in German), Rudolf Wager, Wolfgang Richter, and Herbert Flathe, *Geologisches Jahrbuch*, Vol. 74, 1957, pp. 629–642.

The depth to the interface between fresh and salt water was determined at over five hundred stations by measurement of the apparent electrical resistivity with the four-electrode method. The measurements were carried out to a maximum depth of one hundred meters. The general area investigated lies along the coast of the North Sea between Tergast and Stade. In this region salt water from the coast is encroaching on the fresh ground water. The specific resistivity of 45 ohm-meters was taken as defining the boundary between salt and fresh water. At certain locations interpretation of the resistivity data is ambiguous because clay beds in the area have the same resistivity as aquifers containing salt water. This ambiguity was removed by drilling. Isolated sand lenses containing fresh water were also found to complicate the picture. Most of the measurements, however, are consistent with a relatively clear general picture of salt water encroachment in the coastal areas. The electrical measurements outlined the interface between good and bad water at relatively small expense.

The NaCl content of 440 water-saturated cores with the exception of clay stones plotted against depth showed a broad maximum between two hundred and twelve hundred meters which corresponds to the range in depth of the top surfaces of the salt domes in the area. In the neighborhood of the Reitbrook salt dome, specimens from near the top of the same dome showed greater salinity than specimens taken along the flanks.

The normal salt content of Tertiary sediments in non-salt dome country is compared with that of sediments in Northwest Germany. It is much smaller at depths under a thousand meters. Furthermore, the salinity in non-salt dome country rises slowly with increasing depth, whereas in Northwest Germany it is nearly maximum at two hundred meters, then decreases from five hundred to twelve hundred meters before it rises again to its maximum value. The salt content of formations lying below the interface between fresh ground water and sea water thus seem to correlate with the presence of salt domes.

Victor Vacquier
Scripps Institution of Oceanography
La Jolla, California

Selection of the Best Frequency in Using Inductive Methods of Electrical Exploration, F. M. Kamentskiy, A. A. Kaufman, and Yu. V. Yakubouskiy, *Akad. Nauk. S.S.S.R. Izvestia Ser. Geofiz.*, No. 2, 1957, pp. 200–210.

Choosing a spherical and cylindrical conductor, the authors present the solutions for the electromagnetic response in a homogeneous exciting field. The theoretical part of the paper follows closely the work of Wait (Geophysics, October, 1951, and April, 1952) which they have listed as reference (7). The amplitude and phase of the response for model ore bodies are then measured experimentally and they compare favorably with the computed results. It was found (as predicted by theory) that the amplitude of the response asymptotically approaches its maximum value with increasing frequency, whereas the phase of the response reaches a peak value of some intermediate frequency. The authors conclude that the best operating frequency is just above where the phase anomaly is a maximum.

No attempt was made to estimate the influence of the overburden.

James R. Wait
National Bureau of Standards
Boulder, Colorado

Stockholm Natural Radiocarbon Measurements I, H. G. Ostlund, *Science*, Vol. 126, 1957, pp. 493–497.

The first data reported by the Swedish radiocarbon group, although presenting nothing new in the way of techniques, indicate that the best available techniques have been utilized in setting up this newest addition to the growing number of carbon-14 dating laboratories.

Increasing airborne radioactive contamination due to atomic and hydrogen bomb explosions have forced most of the radiocarbon dating groups to change from the original black carbon method that Libby and his collaborators pioneered to the carbon dioxide proportional-counter method which is not affected by airborne radioactive contamination. The Swedish group has used both methods and favor the latter mainly because of its freedom from airborne radioactive contamination.

The first seven results, of the total of eighty that are given, are samples of known age or samples that have been dated by other laboratories. These cross checks agree extremely well, and, from the agreement between the various radiocarbon dating laboratories, it appears that good absolute ages with small errors can be obtained by this method back to about twenty-four thousand years before the present and that a good indication of the age can be obtained back as far as forty thousand years.

The method is of extreme importance for archeologists, but it is also finding many applications in recent glaciology, as is evidenced by many writers both on this continent and Europe. About 35 results in each of these main fields are given by the Swedish group.

The geological samples are divided into two groups, the first and larger of which deals with submorainic samples and the second with the prehistory of the Baltic Sea. Although time correlations for many of the deposits have been given by normal geological methods, absolute radiocarbon dating cannot but assist the interpretation of the recent past.

H. A. SHILLIBEER
Gulf Research and Development Company
Pittsburgh, Pennsylvania

Structure of the German Alpine Foreland Molasse with the Aid of Seismic Velocities (in German), Horst John, *Erdöl und Kohle*, Vol. 10, 1957, pp. 493–496, 570–573, 661–664.

In this three-part paper Dr. John presents a correlation of geologic structure with seismic velocity for that part of Germany which lies south of the Danube. Within his chosen area, some 100 by 350 kilometers in extent, are 22 wells surveyed for velocity. Using the lithologic and velocity information obtained from these wells, Dr. John works out a sequence of presentations of the velocity variations of the region.

In the first paper of the series, velocity data from the wells are tabulated according to the four geologic epochs represented. A set of maps illustrate in conventional fashion the lateral gradients of average velocity to the various markers chosen. Relationships between the velocity maps and isopach maps are pointed out.

The second part is devoted to an empirical-statistical study of the overburden effect on velocities in the region. A smooth curve is fitted to the interval velocity plot for each well. The set of curves so obtained is considered to represent the normal or overburden increase of velocity with depth. Deviations from these curves are considered to represent lithologic variations of velocity.

The normal increase curves are classified by area since it is evident that the curves form what appears to be a one-parameter family with the velocities decreasing consistently to the northeast.

Using the appropriate normal-increase curve, Dr. John produces a set of "reduced" interval velocities. "Reduced" velocity is to normal velocity at datum as observed velocity is to normal velocity at depth. From the set of reduced velocities, a table is produced giving thicknesses of layers of specified velocity classified by epoch and by well designation. Converted into four frequency-distribution bar graphs corresponding to the four epochs, the reduced velocities are fitted with sets of Gaussian curves and likened to optical spectra. For each epoch, then, each geographical zone has a characteristic or mean, reduced velocity about which all the calculated reduced velocities for that epoch and zone are claimed to be normally distributed.

The concluding part of the paper presents maps of the reduced velocity distributions for each epoch as well as Oligocene and sub-weathering velocity maps. Attempts are made to correlate features of these maps with contemporary deposition patterns, with previously extant overburden, and with the overburden effect of Quaternary ice sheets. It is also shown that sub-weathering velocity gradients are particularly steep along lines of orogenic activity. Another presentation of the reduced velocities

in the form of a cross-section through the length of the molasse emphasizes the extreme complexity of the velocity variations.

Dr. John points out the weakness in his work occasioned by lack of sufficient primary data. He suggests that more data and more analysis can provide more quantitative results. As an ultimate goal of his approach, Dr. John suggests that the depositional history of a section could be read from its velocities.

Dr. John has devised a somewhat novel utilization of seismic velocity data. In this instance this reviewer feels that perhaps the paucity of original data does not justify the extensive analysis performed. On the other hand, the approach is certainly imaginative and intriguing.

CARL H. SAVIT
Western Geophysical Company of America
Los Angeles, California

Exploring the Atmosphere's First Mile, Heinz H. Lettau and Ben Davidson, Editors, Pergamon Press, Inc., New York, 1957, 578 pp. (2 vols.) $20.00.

From 1 August to 8 September, 1953, the Geophysics Research Directorate of the Air Force Cambridge Research Center sponsored the Great Plains Turbulence Field Program at O'Neill, Nebraska. Ten universities or scientific institutions, five Government scientific laboratories or services, and three Air Force Groups for logistical support were involved. The purpose was to obtain maximum scientific return from the concurrent research in the field of micrometeorology. The primary objectives were the study of the profiles of wind, temperature, and other meteorological variables in the lower two thousand meters of the atmosphere; the turbulence structure, boundary fluxes of energy, momentum, and moisture; and the physical soil properties affected by the diurnal variations of meteorological elements.

Volume I contains an introductory article and 65 scientific papers which describe in detail the multitude of instruments used. The last chapter contains data evaluations concerning the heat budget constituents of the earth/air interface, classifications of observations according to convective stability, and non-dimensional analysis of atmospheric boundary layer structure.

In Volume II there are four articles describing the site, the climatology of the region, and the scheduling of observations. In addition, there are detailed tabulations of experimental data which are classified according to seven "General Observation Periods" with an average duration of 25 hours each.

These two volumes contain a wealth of meteorological data and instrumental details, and they represent an invaluable contribution to the literature of meteorology. The direct usefulness of the book to the exploration geophysicist is not obvious. However, since many of the instruments used by geophysicists are subject to error introduced by fluctuations in meteorological parameters at the surface, the data presented and the techniques used could be of great help, particularly in geophysical instrument design.

A. R. KASSANDER
University of Arizona
Tucson, Arizona

PUBLICATIONS RECEIVED

American Journal of Science, v. 256, nos. 1–5 (January–May, 1958)
Annales de Géophysique, v. 13, n. 4 (1957)
Annales de l'Institut de Physique du Globe de Strasbourg, n. 17 (1957)
Annali de Geofisica, v. 10, nos. 1 & 2 (January & April, 1957)
Boletin de la Asociacion Mexicana de Geologos Petroleros, v. 9, nos. 7–12 (July–December, 1957); v. 10, nos. 1 & 2 (January & February, 1958)
Bulletin of the Earthquake Research Institute (Tokyo University), v. 35, part 4 (December, 1957)

Bulletin of the Institute of Nuclear Sciences (Belgrade), v. 8 (March, 1958)
Bulletin of the Research Council of Israel, v. 6B, nos. 1–4 (August–October, 1957)
Bulletin of the Seismological Society of America, v. 48, nos. 1 & 2 (January & April, 1958)
Bulletin of the Seismological Station (Copenhagen), nos. 66–70 (January, 1956–December 1957)
Butsuri-Tanko (Geophysical Exploration), v. 10, nos. 2 & 3 (1957)
Canadian Geophysical Bulletin, v. 10 (December, 1957)
Chronique de l'Union Géodésique et Géophysique Internationale, nos. 7–9 (October & December, 1957; January, 1958)
Deutsche Hydrographische Zeitschrift, v. 10, nos. 3–5 (1957)
Deutsches Hydrographisches Institut Jahresbericht, n. 11 (1956)
Disaster Prevention Research Institute (Kyoto University), nos. 19–22 (March, 1958)
Economic Geology, v. 52, n. 8 (December, 1957); v. 53, nos. 1–3 (January–May, 1958)
Egptian Journal of Geology, v. 1, n. 1 (1951)
Egyptian Reviews of Science, v. 1 (1957)
Erdöl und Kohle, v. 10, n. 12 (December, 1957); v. 11, nos. 1–4 (January–April, 1958)
Geofizikai Közlemények (Budapest), v. 6, nos. 3 & 4 (1957)
Geofysiske Publikasjoner, v. 20, nos. 1, 2, 4, & 5 (August, 1957–January, 1958)
Geological Abstracts, v. 5, n. 4 (December, 1957); v. 6, n. 1 (March, 1958)
Geološki Glasnik (Sarajevo, 1955)
Geophysical Abstracts, v. 171 (October–December, 1957)
Geophysical Digest, v. 5, n. 2 (April, 1957)
Geophysical Journal (Royal Astronomical Society of London), v. 1, n. 1 (March, 1958)
Geophysical Notes (Tokyo University), v. 10, n. 2 (1957)
Geophysical Prospecting, v. 6, n. 1 (March, 1958)
Gerlands Beiträge zur Geophysik, v. 66, n. 4 (1957); v. 67, n. 1 (1958)
Institute of Petroleum Review, v. 12, nos. 133–137 (January–May, 1958)
Journal of the American Society of Safety Engineers, v. 3, nos. 1 & 2 (February & May, 1958)
Journal of Geomagnetism and Geoelectricity (Kyoto), v. 9, n. 2 (1957)
Journal of Geophysical Research, v. 63, nos. 1 & 2 (March & June, 1958)
Journal of the Institute of Petroleum (London), v. 44, nos. 409–413 (January–May, 1958)
Journal of Petroleum Technology (January–May, 1958)
Journal of Technology (Bengal Engineering College), v. 2, n. 1 (June, 1957)
Lucrarile Institutului de Petrol şi Gase din Bucureşti, v. 3 (1957)
Mining Engineering, v. 9, n. 12 (December, 1957); v. 10, nos. 1–5 (January–May, 1958)
Proceedings of the Cambridge Philosophical Society, v. 54, parts 1 & 2 (January & April, 1958)
Quarterly Journal of the Geological Society of London, v. 113, n. 450 (December, 1957)
Report of Department of National Development, Bureau of Mineral Resources, Geology & Geophysics (Australia), nos. 34 & 35 (1957)
Report of Investigations, Department of Mines of South Australia, Geological Survey, nos. 8–10 (1956 & 1957)
Review of Scientific Instruments, v. 29, nos. 1–4 (January–April, 1958)
Rocznik Polskiego Towarzystwa Geologicznego (Krakow), v. 26, nos. 1–4 (1955–1956)
Science, v. 127, nos. 3289–3310 (January 10–June 6, 1958)
Soviet Physics JETP, v. 5, nos. 4–6 (November–December, 1957); v. 6, nos. 1 & 2 (January & February, 1958)
Tellus, v. 9, n. 4 (November, 1957); v. 10, n. 1 (February, 1958)
Transactions American Geophysical Union, v. 39, nos. 1 & 2 (February & April, 1958)
Zeitschrift für Geophysik, v. 23, nos. 5 & 6 (1957)

MEMORIAL

WILLIAM PALMER LAWRENCE

WILLIAM PALMER LAWRENCE died suddenly in Fort Pierce, Florida, on February 6, 1958, of coronary heart disease. He had suffered a severe heart attack in August of 1956, but he was actively at work immediately prior to his death which came as a great shock to his family and many friends. He had been stationed in Fort Pierce for several years as Chief of a seismic field party of the Amerada Petroleum Corporation. He is survived by his wife, the former Loraine Coffelt, and his six-year-old daughter, Lisa Ann, who are now residing in Duncan, Oklahoma; by his mother, Mrs. E. L. Lawrence of Gilmer, Texas; one sister, Mrs. Robert Glasgow of Washington, D. C., and three brothers, Everett L. of Gilmer, Kenneth M. of Tulsa, and Clifton C. presently of Big Timber, Montana.

Willie Lawrence, as he was affectionately known, was born in Gilmer, Texas, on September 23, 1910, the third son of Eunice L. and Valona Morrison Lawrence. After he was graduated from the Gilmer High School, Willie began working in 1930 on a seismic crew of the Geophysical Research Corporation, a subsidiary of the Amerada Petroleum Corporation. He began his career as a geophysicist by learning to do every job on a seismic crew. In 1933 he was transferred to the company's laboratory in Tulsa where he quickly acquired practical knowledge of instrumentation and electronic circuitry. During several years at

the laboratory he also served as a member of a peripatetic velocity survey crew operating from Tulsa. In that work he had ample opportunity to display his unfailing good nature, his ability to work hard under adverse conditions, and his ingenuity in overcoming the instrumental and other difficulties which in those days were the rule rather than the exception.

In 1935 Willie returned to the field organization of the Amerada Petroleum Corporation as an Observer. In that capacity he proved to be exceptionally proficient in developing efficient operating practices and in training men. He had the talents of a mechanical engineer even though he did not possess the formal training. He originated many improvements in apparatus and operating techniques which were quickly adopted by other field crews. In training men he gave short shrift to the lazy and shiftless, but those willing to work and learn found him an able instructor who could not only tell them how to do a job but would show them how best to do it. He asked of his men their very best efforts, but he never expected of them as much as he demanded of himself.

In 1947 Willie Lawrence became the Party Chief of a seismic party which was much used for experimental and pioneering work in difficult areas. This was the type of work that he liked best. He gloried in solving field problems, the tougher the better. As a Party Chief, his interpretative work was of a high order, but he never lost his love for the work in the field. Central Florida and the Edwards Plateau of West Texas were among the difficult areas whose problems engaged his talents.

As a field geophysicist, Willie Lawrence was eminent among those of our profession whose work is all too often overlooked when the kudos for a new discovery are handed out. No mathematical manipulation or interpretation of poor field data can ever replace the dedicated effort of a competent Party Chief.

As an individual, Willie Lawrence was a real gentleman with a warm, engaging personality which reflected the honesty and sincerity of his nature. He asked little of life, and he gave much to others. He met trouble and misfortune with courage and a grin, and he was never bitter. He was profoundly devoted to his wife and daughter.

Willie Lawrence was a warm and loyal friend to many. We miss him greatly; we shall never forget him.

W. T. BORN

TULSA, OKLAHOMA
April 15, 1958

ERRATUM—HENRY CORNELIUS CORTES MEMORIAL

An incorrect statement appeared in the Memorial to Henry C. Cortes in the April, 1958, issue of GEOPHYSICS. Due to an editorial mistake the sentence beginning on the seventh line of page 374 implied erroneously that Henry Cortes was responsible for the initiation of the reflection seismograph method. The intent of the sentence was as follows.

When the Geophysical Research Corporation introduced the reflection seismograph, Henry Cortes was one of the first to recognize its potentialities. Some of the earliest reflection seismograph work was done for Vacuum as a result of his recommendations.

CONTRIBUTORS

F. A. ANGONA

F. A. ANGONA was born in Los Angeles, California, in 1920. From the University of California at Los Angeles he obtained his B.A. degree in 1942 and his Ph.D. in physics in 1953. He has been with the Magnolia Petroleum Company since 1946, except for a three-year period during which he was working on his advanced degree.

LESLIE DUSKA was born in Bartfa, Hungary, on February 5, 1912. He received the B.S. degree from the Ludoviceum (the Royal Hungarian Military Academy) at Budapest in 1934. During the Second World War he commanded a field battalion on the Russian front, and he was later appointed to the Headquarters of the Royal Hungarian General Staff at Budapest. After the war, he was a secretary at the French Military Government's offices in the Rhineland for two years.

For the past ten years he has been residing in Canada, and during most of this time he has been associated with geophysical companies. Between 1951 and 1956, he was a draftsman and computer at the Northwest Seismic Surveys Ltd.; and since then he has been with Exploration Consultants, Inc., in Calgary.

Mr. Duska is an active member of SEG, of the Canadian SEG, and of AAAS.

LESLIE DUSKA

G. H. F. GARDNER

G. H. F. GARDNER was born in Tullamore, Ireland. He has a degree in mathematics and theoretical physics from Trinity College, Dublin, the M.S. from the Carnegie Institute of Technology, and the Ph.D. from Princeton University.

Before joining the Gulf Research and Development Company in 1956, Dr. Gardner taught mathematics both in Ireland and in the United States.

JOSEPH F. GOETZ

JOSEPH F. GOETZ was born at Ayton, Ontario, on July 4, 1935. In 1957 he graduated in engineering physics (with a geophysics option) from the University of Toronto. During his university career he was a pilot in the Reserve Air Force of Canada.

Mr. Goetz was employed for a time in Quebec by Rio Canadian Explorations Ltd. He is now a field engineer with Schlumberger of Canada in Alberta.

WILLIAM C. KNUDSEN

WILLIAM C. KNUDSEN was born in Provo, Utah, on December 12, 1925. After he attended the public schools there, he served in the Signal Corps of the U. S. Army in 1944 and 1945.

In 1950 he graduated from Brigham Young University with a major in mathematics and physics, and he spent the next 4 years at the University of Wisconsin where he received both a master's degree and the Ph.D. in physics.

Since, July, 1954, he has been associated with the California Research Corporation and engaged in geophysical exploration research.

Dr. Knudsen is a member of the American Physical Society and the Society of Sigma Xi.

FRANK J. MCDONAL

FRANK J. MCDONAL received the B.A. degree in physics from Hendrix College in 1940, and he continued his work in physics at the Graduate School of the University of Missouri. In 1942 he was made an Instructor in Physics in the University of Missouri, and in 1944 he joined the Field Research Laboratory of the Magnolia Petroleum Company in Dallas where he is presently employed.

Mr. McDonal is a member of SEG, the Dallas Geophysical Society, the American Physical Society, and the Society of Sigma Xi.

ROBERT L. MILLS received the B.S. degree in electrical engineering from Southern Methodist University in 1943. In 1950 he took the master's degree in the same field from the University of Maryland. From 1943 to 1948, he was at the Naval Research Laboratory in Washington where he was working on equipment and techniques for improving the control apparatus used in aircraft power systems, and two years of this time were spent on active duty with the Navy.

In 1948 Mr. Mills was appointed to the staff of the Field Research Laboratory of the Magnolia Petroleum Company where he was engaged in evaluating newly proposed exploration procedures and in improving those already in use. For two years he directed, under a classified contract with the Office of Naval Research, the development of naval underwater sound detection equipment.

Mr. Mills is now a partner in the Dallas firm of Summers and Mills, Inc. He is a member of the Institute of Radio Engineers, the Acoustical Society of America, and the Institute of Electrical Engineers.

ROBERT L. MILLS

MAURICE PIEUCHOT received the degree of Ingénieur Civil des Mines from the Ecole des Mines de Paris in 1944. Since then he has been engaged in geophysical work with the Compagnie Générale de Géophysique in which he has worked successively as Party Chief, Supervisor, and Chief of the company's seismic department.

M. Pieuchot is a member of SEG, EAEG, and the Association Française des Techniciens du Pétrole.

MAURICE PIEUCHOT

WILLIAM R. RANSONE

WILLIAM R. RANSONE graduated from Southern Methodist University of Dallas in 1930 with a B.S. degree in mathematics. In 1931 he received the M.A. in physics from the University of Texas.

From 1932 to 1934 Mr. Ransone was employed by Geophysical Service Inc. of Dallas. During that time he served some four years in Canada and South America as a Party Chief and later as a Supervisor. Since January of 1942 he has been managing partner of Geochemical Surveys of Dallas.

HENRI RICHARD

HENRI RICHARD received the degree of Ingénieur Civil des Mines in 1933 from the Ecole Supérieure des Mines de Saint-Etienne.

M. Richard has been engaged in geophysical work with the Compagnie Générale de Géophysique since 1934, and during this time he has been successively a Party Chief, a Supervisor, Chief of the company's seismic department, and Chief of the company's methods division.

He is a member of SEG, EAEG, and the Association Française des Techniciens du Pétrole.

R. L. SENGBUSH

R. L. SENGBUSH received his Ph.D. degree in physics and mathematics from the University of Wisconsin in 1944. He served in the U. S. Navy for two years as an electronics officer. Since 1947 he has been associated with the Field Research Laboratory of the Magnolia Petroleum Company.

Dr. Sengbush is a member of SEG and an associate member of AAPG.

GEORGE SHUMWAY

GEORGE SHUMWAY received the B.A. degree from Middlebury College in 1951 and the B.S. and M.S. in geology from the Massachusetts Institute of Technology in 1951.

Since then he has been an oceanographer in the Ocean Floor Studies Section of the U. S. Navy Electronics Laboratory. He has done graduate work in oceanography at the Scripps Institution of Oceanography (University of California) and in geophysics at Harvard University. In 1953 he helped to start a service company, Geological Diving Consultants, Inc.

Mr. Shumway is a member of SEG, AGU, AAPG, GSA, the Acoustical Society of America, and the Society of Sigma Xi.

ROBERT G. VAN NOSTRAND was graduated with a B.S. degree from the Missouri School of Mines in 1942, and, after a period of military service, he returned there as a graduate student and Instructor in Physics and Geophysics and received the M.S. in 1949. He was awarded his Ph.D. by the University of North Carolina in 1953.

From 1948 to 1953 he was employed (on a part-time basis) by the Geophysics Branch of the U. S. Geological Survey. In 1952 he was appointed a Senior Research Technologist for the Field Research Laboratory of the Magnolia Petroleum Company in Dallas to do research in electrical prospecting and in other branches of geophysics. He has recently been made the Chief Geophysicist for the Société de Prospection et Exploitations Pétrolières en Alsace.

Dr. Van Nostrand is a member of SEG, AGU, and EAEG.

ROBERT G. VAN NOSTRAND

KEEVA VOZOFF

KEEVA VOZOFF was born in Minneapolis, Minnesota, in 1928. In 1949 he received the bachelor's degree in physics from the University of Minnesota, in 1951 the M.S. in geophysics from Pennsylvania State University, and in 1956 the Ph.D. in geophysics from the Massachusetts Institute of Technology.

While at MIT he worked on induced polarization (frequency domain) with T. R. Madden and P. G. Hallof, and he held a Morse Fellowship for application of the Whirlwind Computer. In 1955 he moved to Toronto where he has been working in mineral exploration research, first with McPhar Geophysics Ltd., and now with Gresham Exploration Ltd. (Rio Tinto).

Dr. Vozoff belongs to the SEG, EAEG, and the Society of Sigma Xi.

Biographies and photographs of the following authors appear in the earlier issues of GEOPHYSICS as follows: A. R. Gregory, v. 21, p. 213; J. E. White, v. 18, p. 244; G. P. Woollard, v. 20, p. 713; M. R. J. Wyllie, v. 20, p. 969.

SOCIETY ROUND TABLE

COMMITTEES FOR THE YEAR ENDING IN OCTOBER 1958

EXECUTIVE COMMITTEE

President: O. C. CLIFFORD, JR., The Atlantic Refining Co., Dallas, Texas
Vice-President: BEN F. RUMMERFIELD, Century Geophysical Corp., Tulsa, Oklahoma
Secretary-Treasurer: HOWARD E. ITTEN, Empire Geophysical Inc., Ft. Worth, Texas
Editor: LAWRENCE Y. FAUST, Amerada Petroleum Corp., Tulsa, Oklahoma
Past President: ROY F. BENNETT, Sohio Petroleum Co., Oklahoma City, Oklahoma

Nominations

O. C. CLIFFORD, JR., *Chairman*
ROY F. BENNETT
R. C. DUNLAP, JR.

Tellers

J. V. FRANKLIN, *Chairman*

Education

JOSHUA L. SOSKE, *Chairman*
VICTOR J. BLUM, S.J.
P. E. DEHLINGER
G. D. GARLAND
J. W. HOOVER
J. B. HUDSON
V. VACQUIER

Student Membership

W. H. COURTIER, *Chairman*

Subcommittee on Student Membership

FRED J. AGNICH, *Chairman*

Subcommittee on Scholarships

RICHARD BREWER, *Chairman*

Subcommittee on Essays

CHARLES W. OLIPHANT, *Chairman*

Distinguished Lectures

M. E. DENSON, JR. ('58), *Chairman*
R. A. PETERSON ('58)
JOHN BEMROSE ('59)
MILTON BORN ('59)
A. J. HINTZE ('60)
J. WELDON THOMAS ('60)

Radio Facilities

B. D. LEE, *Chairman*
W. M. RUST, JR., *Vice-Chairman*
C. B. BAZZONI
RICHARD BREWER
V. ROBERT KERR
E. M. SHOOK
DANIEL SILVERMAN
BART W. SORGE

Membership

JOHN C. HOLLISTER, *Chairman*
C. L. BARKER
L. H. BOYD
G. A. GRIMM

Honors and Awards

SIGMUND HAMMER ('58) *Chairman*
CURTIS H. JOHNSON ('59)
ROY L. LAY ('60)
PAUL L. LYONS ('61)

Publications

CECIL H. GREEN, *Chairman*
SIGMUND I. HAMMER
H. B. PEACOCK
SIDNEY SCHAFER
ROBERT J. WATSON

Subcommittee on Translation of Russian Publications

IRWIN ROMAN, *Chairman*
EUGENE M. MCNATT
PAUL P. REICHERTZ

Reviews

FRANKLYN K. LEVIN, *Chairman*
W. T. BORN
THOMAS A. ELKINS
W. W. GARVIN
SIGMUND I. HAMMER
CHWAN-CHANG LEE
JOHN E. NAFE
CARL H. SAVIT
V. VACQUIER
JAMES E. WHITE

Geophysical Activity

H. G. PATRICK, *Chairman*
KENNETH L. COOK
R. J. COPELAND
HERBERT HOOVER, JR.
SANTOS FIGUEROA HUERTA
C. N. HURRY
KUMIJI IIDA
C. C. LISTER
L. R. TUCKER

Safety

C. C. SELLERS, JR., *Chairman*
R. N. BRANTLEY
J. W. BROWN
J. W. GREEN
P. M. HANAHEN
R. C. HENDERSON
G. M. KINTZ
W. H. NEWTON
E. L. WELLS

Mining Geophysics

RALPH C. HOLMER, *Chairman*
KENNETH L. COOK
H. V. W. DONOHOO
WALTER E. HEINRICHS, JR.
LEROY SCHARON
R. MAURICE TRIPP
STANLEY H. WARD

Case Histories

DAVE P. CARLTON, *Chairman*

Mining Case Histories

H. LEROY SCHARON, *Editor*

Constitution and Bylaws

W. M. RUST, JR., *Chairman*
CECIL H. GREEN
W. W. HARDY
PAUL LYONS
L. L. NETTLETON

Membership in American Institute of Physics

NORMAN H. RICKER, Liaison Member

Research

W. T. BORN, *Chairman*
F. G. BOUCHER
J. M. CRAWFORD
C. HEWITT DIX
C. H. GREEN
JOHN C. HOLLISTER
L. L. NETTLETON
T. J. O'DONNELL
A. L. PARRACK
R. A. PETERSON
DANIEL SILVERMAN
NOYES D. SMITH, JR.

R. R. THOMPSON
J. E. WHITE
J. P. WOODS

Subcommittee on Thesis Study

L. L. NETTLETON, *Chairman*
C. H. GREEN

Subcommittee on Rice Symposium

NOYES D. SMITH, JR., *Chairman*
C. HEWITT DIX
L. L. NETTLETON
R. A. PETERSON
A. L. PARRACK

Index of Wells

V. U. GAITHER, *Chairman*

Magnetic Recording

J. D. SKELTON, *Chairman*
KEITH R. BEEMAN
ROLAND F. BEERS
K. E. BURG
J. D. EISLER
J. E. HAWKINS
K. M. LAWRENCE
B. D. LEE
G. B. LOPER
R. A. PETERSON
E. B. TICKELL
F. A. VAN MELLE

Magnetic Recording Subcommittee on Definitions & Measurement

L. W. ERATH, *Chairman*
R. A. ARNETT
FRANK COKER
J. M. CUNNINGHAM
J. J. DURAPAU
F. J. FEAGIN
H. R. FRANK
ROGER HARLAN
R. W. KELLEY
L. B. MCMANIS
R. C. MOODY

Magnetic Recording Subcommittee on Recorder Characteristics

S. KAUFMAN, *Chairman*
A. L. PARRACK

American Geological Institute Directors

R. C. DUNLAP, JR. ('58)
ROY F. BENNETT ('59)

AGI Glossary

R. A. GEYER, *Chairman*
L. W. BLAU
D. S. HUGHES
PAUL L. LYONS
L. L. NETTLETON
D. C. SKEELS
I. A. VAN WEELDEN
J. TUZO WILSON

AGI Committee on Licensing

A. E. MCKAY, SEG MEMBER

Business Office

CRAIG FERRIS, *Chairman*
JAMES F. JOHNSON
FRANK E. BROWN

National Research Council Div'n of Earth Sciences Representative

R. D. WYCKOFF

AAAS Council Representative

ROLAND F. BEERS

Radioactive Mineral Exploration

BEN F. RUMMERFIELD, *Chairman*
E. R. GORDON
A. J. HINTZE
JOHN C. HOLLISTER
F. H. LAHEE
PAUL L. LYONS
L. W. MACNAUGHTON
JOHN MASTERS
A. GARCIA ROJAS
STAN. L. ROSE

SEG Committee on IGY

PAUL L. LYONS, *Chairman*

Publicity and Public Relations

BART W. SORGE, *Chairman*
SAM W. ALLEN, JR.
G. A. BOLLINGER
J. M. COCHRANE
S. R. FAUST
STANLEY E. GIULIO
J. A. HALL
GLENN R. HARRIS
B. A. HEIDT
D. T. MCCREARY
W. H. NEWTON
M. L. PUGH
G. A. ROUSSEL
H. B. SMITHWICK
J. C. WATERMAN
RAY H. WRIGHT
W. C. WOOLEY

Sustaining Membership

L. O. SEAMAN, *Chairman*
C. W. PAYNE

LOCAL SECTIONS

Geophysical Society of Tulsa

Chartered February 2, 1948
Frank Searcy, *pres.*
T. S. Green, *1st v-pres.*
F. R. Kittredge, *2nd v-pres.*
P. M. McNally, *treas.*
R. L. Frossard, *editor*
S. E. Giulio, *secty.* The Carter Oil Co., Box 801, Tulsa 2, Okla.
Meetings: Monthly, 2nd Thursday, 7:00 P.M., meeting only, University of Tulsa, room 224, Petroleum Science Hall

Geophysical Society of Houston

Chartered February 14, 1948
John F. Anderson, *pres.*
S. Brooke Stewart, *1st v-pres.*
Paul Farren, *2nd v-pres.*
John R. Monkhouse, *treas.*
Bernard G. Hubner, Jr., *secty.* Atlantic Refining Company, Box 1346, Houston, Texas
Meetings: Monthly, Noon luncheon ($1.65), Rice Hotel

Pacific Coast Section SEG

Chartered April 12, 1948
Dean Walling, *pres.*
Robert B. Moran, Jr., *v-pres., S.D.*
James A. Kurfess, *v-pres., N.D.*
Robert D. Brace, *secty.* Std. Oil Co. of Calif., P.O. Box 278, Oildale, California
Meetings: Monthly, 2nd Thursday, Noon luncheon ($2.00), Biltmore Hotel, Los Angeles

Dallas Geophysical Society

Chartered August 7, 1948
Martin C. Kelsey, *pres.*
John A. Cathey, *1st v-pres.*
Wm. C. Wooley, *2nd v-pres.*
Mark K. Smith, Jr., *secty.* Geophysical Service, Inc., P.O. Box 35084, Airlawn Station, Dallas 35, Texas
Meetings: Monthly, usually 2nd Monday, 8:00 P.M., Fondren Science Building, Southern Methodist University

Fort Worth Geophysical Society

Chartered August 7, 1948
Paul H. Ledyard, *pres.*
L. V. Lombardi, *v-pres.*
Burl J. Boring, *treas.*
H. G. McCleary, *secty.* Woodson Oil Company, 2600 6th Avenue, Fort Worth 4, Texas
Meetings: Monthly, 4th Monday, Noon luncheon ($1.50), Texas Hotel

Ark-La-Tex Geophysical Society

Chartered March 12, 1949
C. P. Bragg, *pres.*
Bill C. Tucker, *v-pres.*
S. T. Spradlin, *secty.* The Ohio Oil Company, P.O. Box 1129, Shreveport Louisiana
Meetings: Monthly, last Monday, Noon luncheon ($1.50), Captain Shreve Hotel, Shreveport

Permian Basin Geophysical Society

Chartered January 30, 1950
B. F. Owings, *pres.*
R. A. Baile, *1st v-pres.*

J. E. Clark, *2nd v-pres.*
J. M. Armstrong, *treas.*
S. L. Hake, *secty.* Box 1018, Midland, Texas
Meetings: Monthly, 2nd Tuesday 7:30 P.M., free coffee & donuts, Midland Women's Club, Midland, Texas

Denver Geophysical Society

Chartered May 19, 1950
R. C. Kendall, *pres.*
J. E. Thompson, *v-pres.*
A. W. Black, *secty.* Continental Oil Company, 1041 Continental Oil Building, Denver 2, Colorado
Meetings: Monthly, 1st Monday, Noon luncheon ($2.35). Petroleum Club, Denver

Canadian SEG

Chartered January 24, 1952
George J. Blundun, *pres.*
John Fuller, *v-pres.*
N. E. Klinck, *secty-treas.* Seismotech Limited, 320—39th Avenue S.E., Calgary, Alberta
Meetings: Monthly, no set schedule

Geophysical Society of Oklahoma City

Chartered September 30, 1952
W. B. Robinson, *pres.*
G. E. Anderson, *1st v-pres.*
R. H. Peacock, *2nd v-pres.*
C. L. Howell, *treas.*
H. R. DeVinna, *secty.* Central Exploration Co., 13 NE 28th, Okla. City, Okla.
Meetings: Monthly, 2nd or 3rd Monday. Time and place to be announced

Casper Geophysical Society

Chartered May 23, 1953
Dupree McGrady, *pres.*
A. C. Austin, *v-pres.*
R. L. Billings, *secty.* Forest Oil Corp., 254 N. Center St., Casper, Wyoming
Meetings: Monthly, 1st Monday, 7:00 P.M., dinner ($2.75), Townsend Hotel, Casper, Wyoming

Geophysical Society of South Texas

Chartered November 9, 1953
W. Harry Mayne, *pres.*
Jack W. E. Edmonson, *v-pres.*
P. J. Rudolph, *secty-treas.* Petty Geophysical Engineering Company, P.O. Drawer 2061, San Antonio, Texas
Meetings: 1st and 3rd Wednesdays, Noon luncheon, Sommers Cafeteria, Main Plaza, San Antonio

Southeastern Geophysical Society

Chartered April 1. 1954
I. B. Murray, Jr., *pres.*
M. H. Dingman, *1st v-pres.*
J. D. Keese, *2nd v-pres.*
Clark E. Allen, *secty-treas.* Geophysical Service Inc., 414 Carondelet Building, New Orleans 12, Louisiana
Meetings: Monthly, 3rd Monday, Noon luncheon ($1.50), St. Charles Hotel, New Orleans

Montana Geophysical Society

Chartered April 12, 1954
Thomas C. King, *pres.*
Ward T. Langstroth, *1st v-pres.*
A. J. Newton, *2nd v-pres.*
N. L. Hull, *secty-treas.* Mobil Producing Company, P.O. Box 2548 Billings, Montana
Meetings: Monthly, 2nd Monday, 7:30 P.M., Billings Petroleum Club

Jackson Geophysical Society

Chartered May 12, 1955
W. J. Robinson, *pres.*
R. C. Cole, *v-pres.*
J. E. MacGregor, *secty.* The California Company, Box 2606, Jackson, Mississippi.
Meetings: Monthly, during 3rd week, 5:30 P.M., refreshments, 6:30 P.M., dinner ($2.00), Roof Garden of Robert E. Lee Hotel, Jackson, Mississippi

Four Corners Geophysical Society

Chartered June 19, 1958
David B. Davidson, *pres.*
R. P. Thomas, *1st v-pres.*
J. W. Rogers, *2nd v-pres.*
V. Frank Hinson, *treas.*
John P. Badami, *secty.* Box 1121, Durango, Colorado

Southwest Louisiana Geophysical Society

Chartered January 4, 1956
Lawrence N. Ott, *pres.*
Neal Clayton, *1st v-pres.*
G. E. Tilley, *2nd v-pres.*
James M. Moore, *secty.* Skelly Oil Company, Lafayette, Louisiana
Meetings: to be announced

Utah Geophysical Society

Chartered October 29, 1956
J. R. Cheney, *pres.*
R. J. Lacy, *1st v-pres.*
D. E. Smith, *2nd v-pres.*
E. W. Morris, *secty.* General Petroleum Corporation, 53 East 4th South, Salt Lake City, Utah

Dakota Geophysical Society

To be chartered
W. E. Phillips, *pres.*
Hugh McCain, *1st v-pres.*
Quin Hayes, *2nd v-pres.*
R. R. Phair, *secty.* Roundup Powder Company, Box 452, Bismarck, North Dakota
Meetings: Monthly, 1st Friday, 7:30 P.M., Petroleum Club, Prince Hotel, Bismarck, North Dakota

New Mexico Geophysical Society

Chartered September 18, 1957
W. B. Scaife, *pres.*
J. A. Hall, Jr., *1st v-pres.*
R. A. Nixon, *2nd v-pres.*
E. J. Medley, *secty-treas.* Magnolia Petroleum Company, 714 Roswell Petroleum Bldg., Roswell, New Mexico

STUDENT SOCIETIES AFFILIATED

Colorado School of Mines Society of Student Geophysicists

Ernest Berkman, *secty.* Department of Geophysics, Colorado School of Mines, Golden, Colorado
Meetings: Monthly, 2nd Monday, 4:00 P.M.

Geophysical Society of Saint Louis University

Wm. Reeves, *secty.* Saint Louis University, 3621 Olive Street, St. Louis 8, Missouri
Meetings: Monthly, 2nd Wednesday 7:30 P.M., meeting only, Institute of Technology

SEG Houston Student Section

Reed B. Kubena, *secty.* Box 6527, Houston, Texas
Meetings: to be announced

University of Toronto Geophysical Society

John E. Hogg, *secty.* 49 St. George Street, Toronto 5, Ontario
Meetings: Bi-weekly, alternate Thursdays, 4:00 P.M., 49 St. George Street

University of Tulsa Student Geophysical Society

Hugh Hayes, *secty.* Department of Geophysics, 600 South College, Tulsa, Oklahoma
Meetings: Weekly, Thursday, 4:00 P.M., Petroleum Science Bldg.

Trans-Pecos Student Section

John T. Sample, Jr., *secty.* Box 56, Texas Western College, El Paso, Texas
Meetings: to be announced

Pennsylvania State University Geophysical Society

Wm. R. England, *secty.* College of Mineral Industries, University Park, Pa.
Meetings: to be announced

University of Utah Geophysical Society

Harry D. Narans, Jr. *secty.* College of Mines and Mineral Industries, Salt Lake City 1, Utah
Meetings: Monthly, 1st Thursday, Noon, Mines Building. Other special meetings to be announced

A & M College of Texas Student Geophysical Society

Edward C. Hanson III, *secty.* Geology and geophysics dept., A & M College of Texas, College Station, Texas

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with Bylaws, Article III, Section 4. References are listed in parentheses following the name of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Howard H. Adkinson (C. C. Lawrence, J. S. Hopkins, M. C. Born, B. W. Wallace)
Wilbur E. Allison (T. J. O'Donnell, Sigmund Hammer, George R. Watson, J. Brooks Parkhill)
Herman C. Baker (H. V. Goss, O. K. Fuller, Jr., D. B. Moore, A. A. Moore, Jr.)
Marvin E. Bass (J. A. Hall, Jr., James F. Johnson, J. C. Lusk, Joe H. Jones)
Aubrey J. Bassett (R. C. Cole, W. A. Allred, W. W. Ogden, P. E. Eisenstatt)
William Earl Bell (Donald M. Wagg, Joshua L. Soske, A. A. Brant, K. E. Hunter)
R. C. Bostrom (Norman J. Christie, John Legge, L. P. Geldard, N. K. Moody)
Donald C. Burtt (Gordon R. Hess, W. L. Irwin, A. A. M. van Dijk, J. F. Wright)
Edward C. Clark (W. H. Wurth, S. R. Marsh, W. E. Dawson, G. E. Olson)
William G. Couch (Helmi F. Sagoci, J. W. Hoover, H. E. Stommel, L. E. Reilly)
Leslie F. Dunlap (J. Lee Davis, Darrel W. Boyd, Richard G. Martin, Orley E. Prather)
E. F. Glenn (A. V. Thompson, C. B. Scott, G. E. Olson, G. R. Perkins)
K. D. Huckabee (W. P. Scaife, R. V. Smith, M. C. Wicker, J. S. Rhodes)
Perry Howard Hunnicutt (Thomas A. Garvey, B. F. Harmon, I. J. Reed, S. Zimmerman)
David Q. Loepp (R. L. Billings, A. C. Austin, Wesley H. Farmer, Wendall H. Hawkes)
William J. Masterson (J. Bentley-Llewellyn, G. D. Jett, Carl W. Blakey, Ben F. Rummerfield)
Mary Joyce O'Brien (T. J. O'Donnell, Sigmund Hammer, L. W. Gardner, G. R. Watson)
Harry W. Parent (E. V. McCollum, Craig Ferris, J. G. Knowles, T. G. Arnold)
A. J. Peissel (E. F. Stratton, J. Bulhon, F. P. Kokesh, E. G. Leonardon)
Jack J. Richard (Alton McClung, J. P. House, D. B. Cocovinis, W. C. McGinnis)
Frank J. Sander (C. F. Moore, Jr., L. J. Larquier, M. P. Tixer, F. P. Kokesh)
David George Schweitzer (R. E. Lawson, F. A. Grimm, R. P. Warren, F. B. Graham)
Leonard B. Steele (Mark D. Butler, Sargent F. Jones, II, D. E. Cook, J. E. McGee, H. E. Harris)
John F. Tolk (W. Lee Moore, P. J. Radolph, Weldon Crawfore, P. E. Narvarte)
Hugh O. Walker, Jr. (B. D. Lee, A. L. Parrock, N. J. Lea, Frank Press)
W. C. Walker (T. O. Harkness, C. E. McKenzie, A. P. Mehringer, Herbert Schlundt)

APPLICATION FOR TRANSFER TO ACTIVE MEMBERSHIP

L. R. Book, Jr. (L. Y. Faust, Sam D. Rogers, John R. Robbins, Russell H. Talty)
Raymond R. Bristow (J. H. Dunaway, D. H. Gardner, J. A. Smith, C. C. Palmer)
Jorge E. Castillo (J. A. Harris, T. O. May, R. R. Kitch, J. E. MacGregor)
George D. Ferrell (K. E. Baer, R. S. Mahannah, R. F. Zimmerly, P. I. Bediz)
Robert F. Gregory (O. K. Fuller, Jr., W. M. Rust, Jr., H. G. Patrick, O. D. Brooks)
John M. Lankton (J. E. Spencer, E. A. Krieg, Jr., Ben R. Howard)
Donald P. Lowe (W. W. Clark, Marvin Romberg, James Watson, J. T. Williams)
R. J. McCaffrey (A. N. McDowell, J. M. Desmond, W. A. Knox, C. J. Chapman)
K. B. Mickelson (Paul C. Reed, Castle J. Harvey, Robert R. Bartel, Gordon E. Jacober)
Ernest G. Miller (D. M. Sawtelle, R. W. Cowden, R. H. Carter)
Raymond E. Miller (Henry R. Joesting, Louis C. Pakiser, Jr., Rudolph A. Black, P. Edward Byerly
Albert E. Rettig (M. A. Knock, F. H. Hammons, H. F. Patterson)
W. J. Rieker, Jr. (Otis B. Hocker, T. L. Kunkel, Alton McClung, J. P. House, L. V. S. Roos)
Dewey D. Young (Ralph Howe, E. V. McCollum, Craig Ferris, T. G. Arnold)

GEOPHYSICS, VOL. XXIII, NO. 3 (JULY, 1958), PP. 606–623, 8 FIGS.

A GRAVITY INVESTIGATION OF A SULPHIDE DEPOSIT*

JOSEPH F. GOETZ†

INTRODUCTION

The application of gravity methods to investigations of small-scale subsurface features has not yet paralleled large-scale structural investigations such as regional surveys and oil explorations. The problems involved in a gravity survey which searches for the location of an ore body, or some small structural feature, are mainly similar to those of the large-scale case, but they are possibly somewhat more difficult due to the size of the anomaly. When such small anomalies are involved, the geophysicist may often run into the difficulty that the errors in the work are of the same order as the expected anomaly. Despite other disturbing factors related to the topography and densities of the materials involved, gravity surveys carried out on local rather than on regional scales can be very important in the location of small structures and ore bodies.

The purpose of this essay is to present the results of a gravimeter survey carried out by the author over a body of massive sulphides. Some of the problems encountered and techniques used are discussed.

The sulphide body was found by truck-borne electromagnetic equipment late in 1954 and was named "Anomaly 96" by its discoverers, Rio Canadian Explorations Ltd. It is located in Dufresnoy Township, Quebec, approximately 20 miles north-northwest of Noranda. It is now held by Mobrun Copper Mines Ltd., a company formed to exploit the deposit.

GEOLOGICAL DATA

The area is overlain by glacial till and clay to varying depths, but much geological information was obtained by examination of drill cores.

The sulphide mass occurs as a replacement of sheared rhyolite on a rhyolite-basic tuff contact. The rocks to the south are rhyolites, rhyolite breccias, and rhyolite tuffs, while those to the north are mainly basic volcanics. Disseminated pyrite occurs in both walls spreading out as much as 100 ft. A highly sheared dyke follows the sulphide body along and beyond its whole length. There is some evidence of a drag fold through the center section.

The mineralization is characterized by two types of pyrite, the most abundant being a very fine-grained "cherty" pyrite containing finely divided sphalerite while chalcopyrite occurs on joint planes and in areas of brecciation of the pyrite. The other type of pyrite is very coarse, and it contains chalcopyrite intimately mixed with it. This type of ore occurs only on the south side of the body.

* Prize Essay for 1957 in the Annual Student Essay Contest. Manuscript received by the Editor December 26, 1959.

† Schlumberger of Canada, Drayton Valley, Alberta.

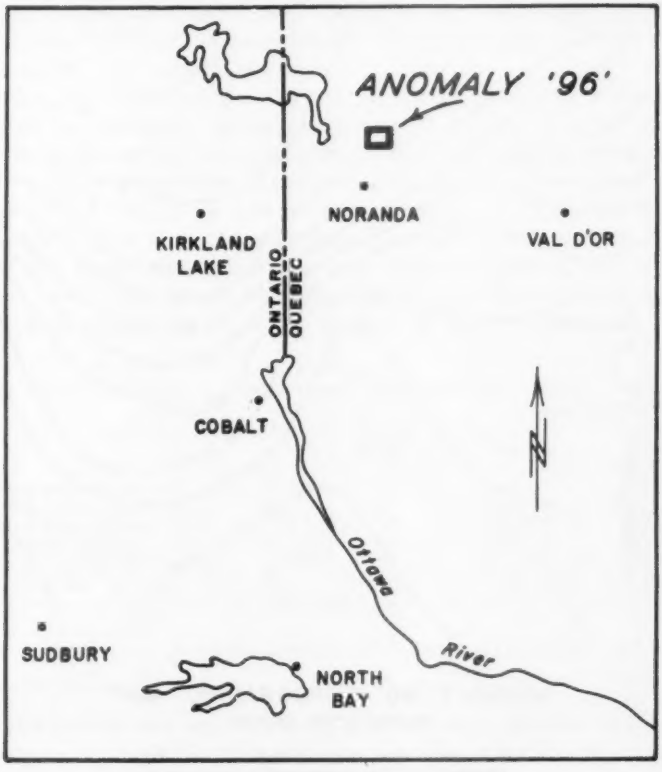


FIG. 1. Map showing location of Anomaly 96.

DESCRIPTION OF WORK CARRIED OUT

A grid network was laid out over the area surrounding the sulphide body. A base line of 2,400 ft was laid out in a true east-west direction conveniently along the side of a road. Nine straight-line traverses, each of 2,000 ft, were laid out in a true north-south direction at right angles to the base line. The layout is shown in Figure 2. Gravimeter stations were established at 100-ft intervals along these lines for a total of 205 stations. The survey covered an area considered more than adequate to cover any anomalous effects of the ore body. The outer lines were located at a distance far enough from the ore so that they could be used in density determinations as outlined below.

The elevations of all the stations relative to a base station were determined by means of a spirit level. All the elevation loops closed to within 0.1 ft. The error involved due to the elevations, then, was less than ± 0.01 mg. A contour

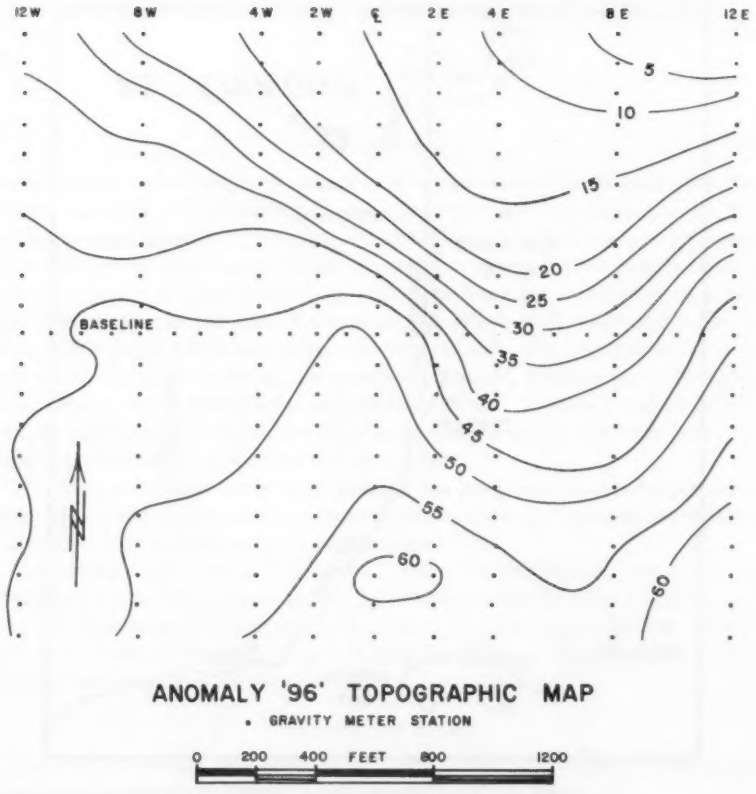


FIG. 2. Topographic map of Anomaly 96. Contour interval 5 ft.

map of the topography was plotted from these data (Figure 2). The maximum topographic relief was 55 ft.

Gravity measurements were carried out with a Worden gravimeter, having a scale constant of 0.10742 mg per scale division. The observed values were corrected for diurnal drift. This correction embraces both meter drift, due to temperature variations, and tidal effects. Throughout the reading of gravity, drift was checked approximately every 45 minutes by reading the base station or other stations at which drift had already been determined. In this way, it was hoped that drift errors could be cut to a minimum.

ROCK DENSITIES

It is evident that density variation below the surface is a primary factor in the consideration of the magnitude and type of gravity anomaly which might

be detected by gravity measurements. In fact, gravitational exploration depends on the existence of density contrasts between geological bodies and the surrounding material in a horizontal direction.

The densities of different types of rock materials involved in the survey were determined by means of a simple specific gravity balance constructed by the author. As wide a variety as possible was chosen from samples available from drill cores. These measurements supplied good representative figures for the densities of field rock in the area as well as for the ore. The materials were divided into 6 general groups according to geologic characteristics. Average densities were found for each of these groups. There were considerable variations in density, even in the specific zones and especially in the massive pyrite. The results of these density determinations are listed in Table 1, below.

TABLE 1

Zone	No. of Samples	Density (gm/cc)	
		Range	Average
Country rock south of ore body	30	2.63–2.77	2.70
Country rock north of ore body	83	2.64–2.78	2.70
Lamprophyre dyke material	13	2.72–2.84	2.78
Massive sulphide material	83	4.08–4.98	4.63
Heavy disseminated to coarse pyrite	30	3.51–4.21	3.80
Disseminated pyrite	51	2.75–3.48	2.96

CORRECTIONS APPLIED TO OBSERVED GRAVITY MEASUREMENTS

Reduction to Datum

The raw gravity data were corrected for various large influences on the meter measurements. A datum elevation was chosen and the measured data were corrected relative to this plane. Corrected gravity values represent readings which would be obtained if the meter were set on the datum plane.

The first of these corrections is the "free air" correction. This factor accounts for the decrease of the force of gravity with increase of elevation (increase in distance from the center of the earth). The "free air" correction has been calculated to be 0.09406 mg/ft, and it must be added to stations at an elevation higher than datum.

The Bouguer correction takes into account the attraction of the material between the datum and the individual station. This correction considers the effect as being due to an infinite slab of material between each station and the datum. It is equal to $2\pi G\rho h$ where

G is the gravitational constant,
ρ is the density in gm/cc,

and

h is the distance above datum in ft.

The Bouguer correction is always opposite in sign to the free-air correction.

Since both the free-air and the Bouguer corrections are simple constants multiplied by the elevation differences, it is common practice to combine the two effects into a single factor known as the elevation correction.

The most straightforward way of determining the elevation factor is to substitute, into the Bouguer correction, an average value for the density of the country rock in the area. Using 2.70 gm/cc as an average density, the elevation correction is 0.05954 mg/ft. An examination of the resulting residual gravity map cast some doubt as to whether or not this was the best possible figure for the factor.

The choice of a figure for the density in the Bouguer correction is a rather critical one. In a distance of 50 ft between station to datum an error of 0.10 in the density would result in a gravity error of 0.06 milligals. It is a very difficult task to obtain an accurate determination of the density of unconsolidated overburden material. From drilling information, accurate densities of bedrock materials were determined but the value used in the Bouguer correction must represent an average of the entire slab of material from the station down to datum.

A method has been outlined by Nettleton whereby the effective density of a section of earth materials can be determined. In this "density profile" method, a traverse of gravimeter stations is run across a local topographic irregularity, preferably a hill, a valley, or both. The observations are then reduced using various densities in the Bouguer correction. Profiles of gravity are then plotted and compared to the topographic profile. If the density chosen is too small, the profile of the Bouguer gravity will reflect the topographic feature. If it is too large, the feature will be reflected in a negative sense. The best value for the density is that which exhibits a minimum correlation between the reduced gravity and the topographic irregularity.

The traverse chosen must be located near enough to the anomaly so as to be characteristic of the area around the anomaly and yet far enough away so as not to be influenced by it. Lines 12E and 8E were chosen.

The results of these extended and laborious calculations indicated a density of approximately 2.71 gm/cc, although it became quite difficult to distinguish between a few of the profiles corresponding to densities close to this one. This would appear to be proof that the value for density chosen originally was almost correct. The objectionable characteristics of the residual gravity map can probably be explained by variations in overburnen thickness, as will be discussed later.

The Nettleton Method has the disadvantage that a best fit must be estimated by the computer. Several analytical methods have been proposed, aimed at eliminating personal estimation. However, after a consideration of the excellent agreement achieved between the first two methods, it was deemed unnecessary to attempt another method.

Terrain Correction

Local irregularities in the topography have appreciable effects on gravimeter readings and must be taken into account for accurate reduction of the gravity values. Hills rising above the level of the station will produce an upward component of gravity, while valleys below the station result in a loss of downward components as they invalidate the assumption of an infinite plane sheet in the Bouguer formula. The usual procedure for calculating the effect of rough terrain is a zone chart method presented by Hammer (1939). This chart is drawn on a transparent sheet to the same scale as the topographic map and is superimposed on the map with its center at the gravity station to be corrected. The average elevation in a zone, relative to the station, is determined, and the effect of this zone, in mg, is taken from a set of tables. The correction is always added. When the method was applied to this survey, it was found that nearly all of the stations possessed only minor topographic irregularities whose effect on the gravimeter was so small that they could be neglected.

Regional Correction

The elevation factor having been determined, the corrections were added to the raw gravity values to give the reduced relative gravity or the Bouguer gravity. These reduced data were plotted in profiles along the traverses. An isanomalic contour map was also constructed from this information as seen in Figure 3. A closed anomaly is revealed by the map, as well as a positive northeasterly gradient.

The gravity observed at a station is the measurement of a summation of effects. It is the resultant of all gravitational attractions within the range of the instrument. The contour map in Figure 3 is considered to be made up of two generalized parts, a regional and a residual effect. The regional effect is due to a field that is too broad or too great in relief to be a possible expression of a structure of interest. It is usually assumed to be smooth and regular, as though due to a deep-seated disturbance. The residual anomaly is the residue left after subtraction of an estimate of the regional effect.

Mathematically,

$$\Delta g = g(0) - \bar{g}(r)$$

where

Δg is the residual value,
$g(0)$ is the station gravity value,
$\bar{g}(r)$ is the average gravity for the area within a radius r from the point where the station value was obtained.

The choice of the regional will obviously determine the nature of the residual map. Nevertheless, this choice is very largely empirical. In relatively simple cases, the selection of a regional is an easy matter, and different men will make about the same choice. However, when the regional effect is complicated, the

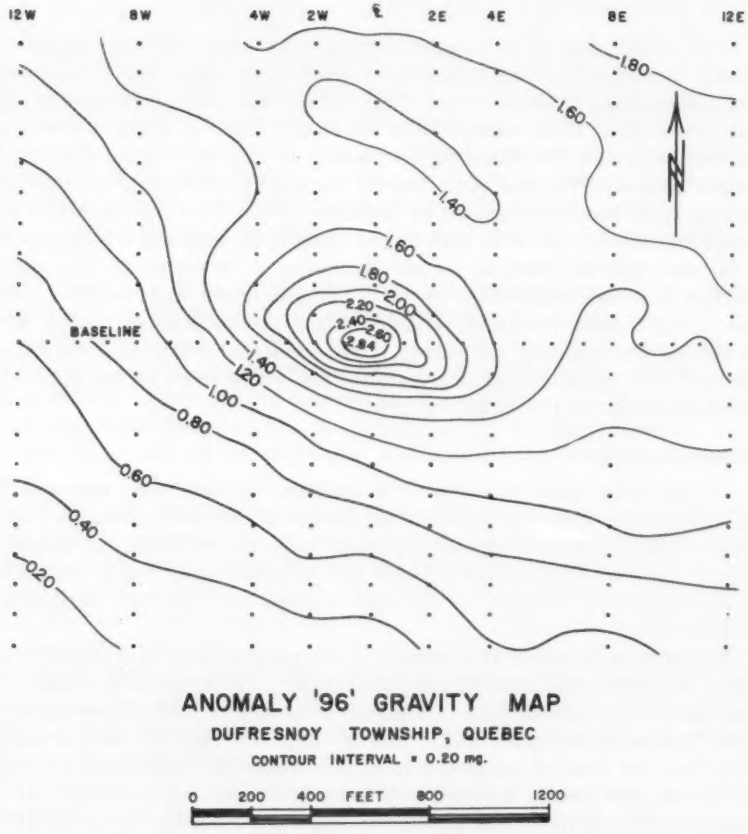


FIG. 3. Bouguer gravity contour map of Anomaly 96.

selection becomes quite difficult, and no two people are likely to arrive at the same solution.

There are several methods available for the removal of the masking effect of the regional gravity. One technique involves drawing smooth gravity contours on the map, in a manner which appears best to represent the regional gravity picture. Departures between the observed gravity contours and the regional contours represent local gravity values. This system is rather outmoded now, since it depends too much on personal judgement.

In the "average value" method, the regional effect at a certain point is taken to be the average of the values of the total field at a number of points distributed symmetrically about the point. Although the geometric pattern which controls

the number of points averaged is not too important, the dimensions of the figure are quite critical. As a result, the size of the residual anomaly may depend to a large extent on the interpreter.

Several numerical analyses have been suggested for the regional correction, and they are intended to do away with the personal equation.

Considering the small area and the sharp character of the anomaly involved in this particular case, it was decided that the most convenient method to use would be the "profile" method. Profiles of gravity values had been plotted along north-south and east-west lines. Straight-line approximations were drawn on these profiles to represent the regional effect, which was then subtracted from the observed value at each station. In effect, removing the regional amounted to subtracting, from the observed values, a plane surface of gravity values striking N. 64° W. and dipping 19° south west. To obtain the residual map, a gradient of 0.60 mg per 1,000 ft in a north-south direction and 0.35(4) mg per 1,000 ft in an east-west direction was removed.

Figure 4 shows the gravity map after the gradient has been removed. The obscure swirls of the uncorrected map resolve themselves into a closed, clearly defined anomaly superimposed on a relatively smooth background. The magnitude of the anomaly is over fifty times the probable error of a single observation, so there can be no doubt of its significance. It must be the expression of a well-defined local subsurface feature.

A study of the residual map shows an area of high force of gravity in the northwest part, while marked lows appear in the southeast and northeast sections. A sketchy idea of the overburden thickness was obtained from drilling information. These drill holes are widely spaced and cover only a relatively small section of the total area so that these data are not very reliable. Nevertheless, the information does reveal a shallow overburden in the central to northwest region. Also there is evidence that the overburden deepens rapidly as one proceeds northeast in the vicinity of line 4E, 600 ft north of the base line. No proof of its thickness is available for the southeast area, but since the terrain is high, but very wet, one might expect that the layer of impervious glacial clay is abnormally thick. The characteristics of the residual map show a definite correlation to these observations and assumptions.

DETERMINATION OF TONNAGE

One of the primary answers that such a survey is expected to provide is a figure for the size of the ore body in terms of the tonnage of ore present.

A simple method for carrying out this calculation is to assume some simple shape for the ore body, such as a sphere or cylinder, and, from formulae provided by textbooks, to calculate the mass required to cause the observed anomaly directly over the body. However, few ore deposits fall into the category of a sphere or a cylinder; this approach must thus be rejected when an accurate result is required.

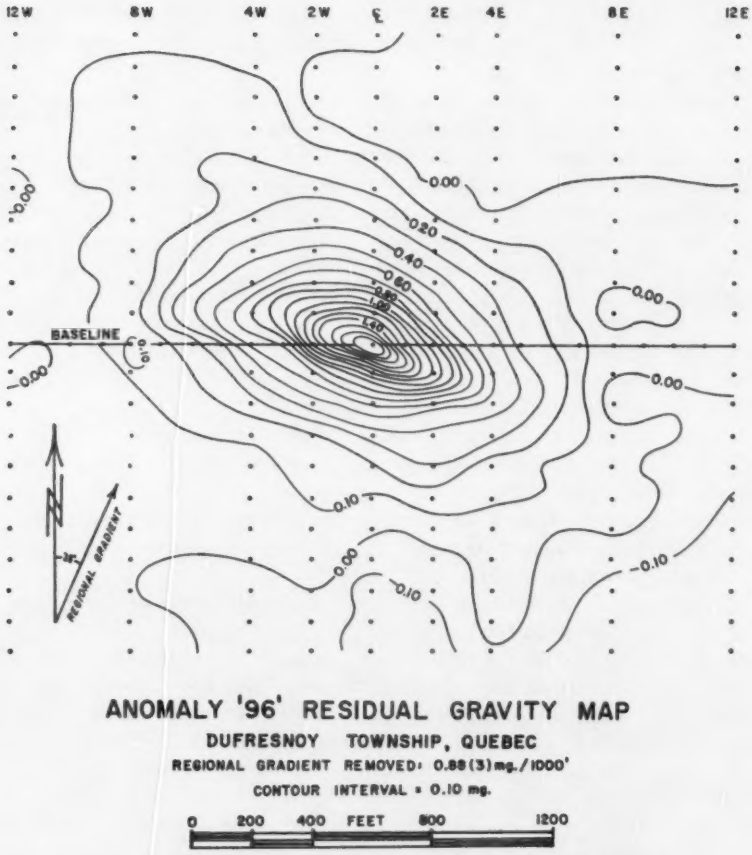


FIG. 4. Anomaly 96 residual gravity map. Direction and magnitude of regional correction are indicated.

A preferable method for calculating tonnage is based on a combination of the Gauss Divergence Theorem and Poisson's Equation for gravitational potential. Gauss' Theorem states that for any continuous function $V(x, y, z)$,

$$\int_v \operatorname{div} V dv = \int_s V \cdot n ds.$$

But

$$\vec{V} = \overrightarrow{\operatorname{grad}}\, U,$$

where U is the gravitational potential function due to a mass distribution in the volume V.

For an external point P,

$$U_P = G\int_v \frac{\rho dV}{l}$$

where

G is the gravitational constant,
ρ is a density function of the mass distribution,
l is the distance from a mass element to the point P.

$$\therefore \quad \int_v \nabla^2 U dv = \int_s \frac{\partial U}{\partial n} ds \tag{1}$$

where $\partial U/\partial n$ is the force component normal to the surface S.

Now, introducing Poisson's equation,

$$\nabla^2 V = -4\pi G\rho$$

and substituting into equation (1),

$$-4\pi G\int_v \rho dv = \int_s \frac{\partial U}{\partial n} ds, \qquad \int_s \frac{\partial U}{\partial n} ds = -4\pi GM. \tag{2}$$

This equation is valid at all points exterior to the surface S. But the surface S is not required to be the actual surface that bounds the mass. The Gaussian surface is normally taken to be a sphere, although it can be any closed surface. In the case of a gravitational computation we may choose a large hemisphere whose flat surface lies parallel to the datum plane, as illustrated in Figure 5. As the length of the radius approaches infinity, the normal force $\partial U/\partial n$ is represented

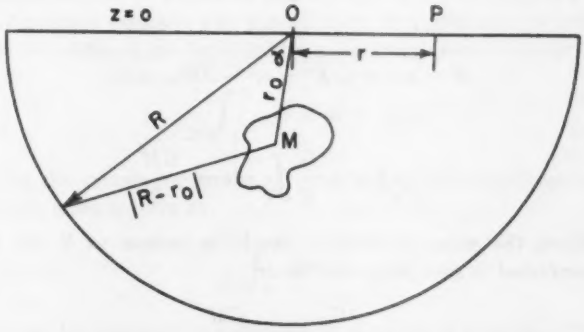


FIG. 5. Diagram showing the Gaussian Surface.

by the vertical component of gravity $\partial U/\partial z$, i.e., the negative of the quantity measured by the gravimeter.

To evaluate the surface integral in equation (2), it is advantageous to divide it into two parts corresponding to the flat and curved surfaces.

$$\int_s = \iint_{z=0} + \iint_{R=\text{const.}}$$

(a) $$\iint_{z=0} \frac{\partial U}{\partial n}\, ds = \iint \frac{\partial U}{\partial z}\, dxdy.$$

In the limit, as R approaches infinity, (a) becomes

$$-\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)dxdy$$

where $g(x, y)$ is the quantity measured by the gravimeter.

Using spherical polar coordinates,

(b) $$\iint_{R=\text{const.}} \frac{\partial U}{\partial n}\, ds = \int_{\phi=0}^{2\pi}\int_{\theta=\pi/2}^{\pi} \frac{\partial U}{\partial R} R^2 \sin\theta d\theta d\phi$$

where

$$\phi = \text{longitude},$$

and

$$\theta = \text{co-latitude}.$$

For a point Q on the surface of the hemisphere,

$$U_Q = G\int_v \frac{\rho_Q dv}{|R - r_0|}$$

where

$$|R - r_0| = \sqrt{R^2 + r_0^2 - 2Rr_0\cos\gamma}.$$

Now,

$$\lim_{R\to\infty} U_Q = \frac{G}{R}\int_v \rho dv = \frac{GM}{R}.$$

So, for $R \gg r_0$, the mass distribution tends to behave as if the whole mass were concentrated at one point, and hence

$$\frac{\partial U_Q}{\partial R} \to -\frac{GM}{R^2}.$$

Then (b) becomes $-2\pi GM$.

Therefore, combining (a) and (b), we have

$$-\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)dxdy - 2\pi GM = -4\pi GM$$

or

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} g(x, y)dxdy = 2\pi GM.$$

Introducing plane polar coordinates

$$\int_{r=0}^{\infty}\int_{\theta=0}^{2\pi} g(r, \theta)rdrd\theta = 2\pi GM. \tag{3}$$

Finally,

$$M = \frac{1}{2\pi G}\int_{r=0}^{\infty}\int_{\theta=0}^{2\pi} g(r, \theta)rdrd\theta. \tag{4}$$

Ideally, the effect of an anomalous mass will approach zero as r approaches infinity. But from a practical standpoint, beyond a certain radius $r=R$, the disturbance due to the body is so small that it may be neglected. That is, at some distance from the origin, g is less than some arbitrary value ϵ. The determination of this radius is somewhat empirical, but its value is not very critical. As a result of this approximation there will be a remainder term introduced, and equation (4) becomes

$$M = \frac{1}{2\pi G}\int_{0}^{R}\int_{0}^{2\pi} g(r, \theta)rdrd\theta + R_e \Big| \begin{matrix} g < \epsilon \\ r > R. \end{matrix} \tag{5}$$

This integral cannot be evaluated directly. But it can be simplified somewhat by the use of average values of g at various radii. It is seen that $\bar{g}(r)$, the average value of g at the radius r, can be found by integrating around the circle

$$\frac{1}{2\pi}\int_{0}^{2\pi} g(r, \theta)d\theta = \bar{g}(r).$$

Neglecting the remainder term and introducing this simplification, the expression for the mass reduces to

$$\frac{1}{G}\int_{0}^{R} \bar{g}(r)rdr.$$

To evaluate this integral it is necessary to construct a zone chart. The area is divided into zones by means of circles and radial lines. Drawn on transparent

paper, this chart is placed on the residual gravity contour map, and the average value of the force of gravity in each annular ring (r_s to r_{s+1}) is determined. Clearly then, the value of the integral is the summation of the effects of these rings.

Equation (6) offers a simplified method for calculating the mass

$$M = \frac{1}{G} \sum_{r_s=0}^{R} \bar{g}(r_s, r_{s+1}) \int_{r_s}^{r_{s+1}} r dr$$

$$M = \frac{1}{G} \sum_{r_s=0}^{R} \bar{g}(r_s, r_{s+1}) \tfrac{1}{2} [r_{s+1}^2 - r_s^2]. \qquad (6)$$

The radii of the circles were chosen to increase by 100-ft intervals to the maximum radius of 900 ft. The tonnage calculated by this method proved to be 3.19 million tons. Since the gravity readings are affected by the disseminated pyrite present in the wall rock, the figure given may be expected to be a small amount higher than the actual tonnage of massive sulphides.

ESTIMATION OF SIZE AND SHAPE

Reliable quantitative interpretation of gravity information requires not only accurate data and a good estimation of regional disturbances, but it also requires sufficient additional control to limit the variables involved in the shape and position of the anomalous body. A given buried mass will produce a definite predictable gravity effect at any chosen point on the surface. However, the prediction process is not readily reversible. From the standpoint of physical interpretation alone, a given gravity anomaly could be produced equally well by an infinite number of possible mass distributions. A gravity anomaly is always wider than the mass anomaly that produces it; also an indication of the depth of the mass can be derived from the gravity profiles. Other than these, the gravity picture gives no discrimination.

Because of the lack of uniqueness, the usefulness of an analysis depends on the amount of control available to limit the inherent ambiguity in the determination of the mass distribution which can cause a given gravity effect. Often the geophysicist has information other than gravity data on which to base his interpretation. Many of the theoretically possible solutions may be ruled out by information obtained from drilling, from other geophysical data, or from geological data.

In this case, there is a considerable amount of auxiliary control available in the form of drilling data. This information indicates an elongated tabular or lens-shaped body dipping almost vertically. The deposit is generally parallel to the surface, almost 1,000 ft in length, and a maximum of 600 ft deep. The body tapers off in both directions, although the majority of the mass lies to the west of the center. Depth of overburden is shown to be quite constant over the extent of the deposit.

The residual contours seem to indicate that the body is narrow and fairly straight. Since the contour figure is narrower at the east than at the west, but nearly as steep, the body could be expected to taper off somewhat more to the east, but not to plunge appreciably in either direction. It is necessary to point out that these predictions would not have been valid on the grounds of gravimetric evidence alone.

The gravity anomaly can best be studied by means of cross-sections and a lengthwise section. The lengthwise section was taken roughly in the direction of elongation of the contours, i.e., N. 62° W. This direction should be approximately that of the elongated direction of the ore body. An examination of the lengthwise section reveals that the anomaly tapers off smoothly from its highest point at the center, dropping off more sharply to the east than to the west. This could be taken to mean that the body pinches out towards both ends, but more rapidly to the east. The lengthwise section also suggests a length of about 800 to 1,000 ft. The center cross-section gives evidence that the disturbing mass is perhaps 150 ft wide, while other cross-sections at various distances from the center exhibit a decreasing anomalous effect with distance until at 600 ft from the center very little disturbance is recorded.

The method of establishing the mass distribution followed the indirect approach of computing the effect of an assumed mass, based on the auxiliary control available, comparing the computed with the observed effect, modifying the mass distribution and recomputing the effect, etc. This process is carried on until the observed and calculated profiles agree within certain limits. There is, of course, a practical limit to the time spent on these calculations. It must also be remembered that achievement of a good fit between computed and observed effects is not proof of the reality of the mass distribution used unless auxiliary control is adequate.

Available information suggests that this ore body can be placed in the class of "two dimensional" bodies, i.e., those involving structures which extend to infinity in one direction, lie parallel to the surface, and whose cross-sections are unchanging along their infinite length, Obviously, the body is not infinitely long, but a table of "end corrections" given on page 117 of Nettleton's textbook was used to correct for this. Neither is the cross-section constant along its entire length. This problem was solved by approximating the body as a configuration made up of several rectangular segments of different lengths and shapes, each having a uniform cross-section throughout its length. In this way, the "pinching out" characteristic of the body could be approximated by allowing the outer sections to consist of only one slender block, while the region near the center was built up by additional blocks.

The cross-sections of the ore body can best be approximated by vertically elongated rectangles. Each of the segments may be regarded as a vertical sheet. The gravitational effect of such a structure has been calculated by Nettleton (1942).

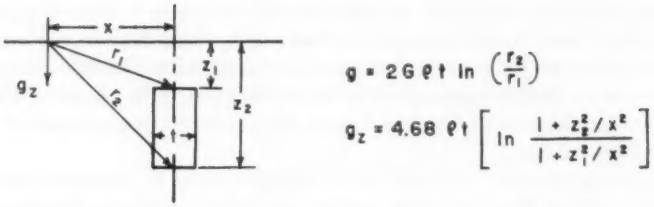


FIG. 6. Diagram showing the gravitational effect of a vertical sheet.

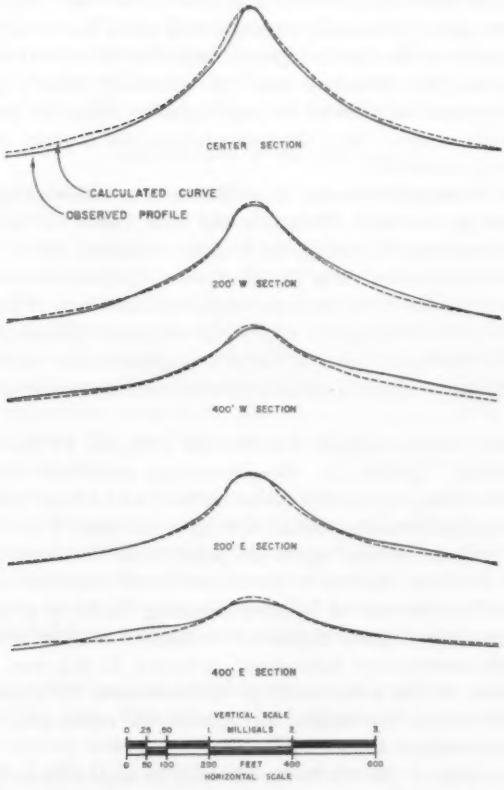


FIG. 7. Comparison of calculated curves caused by the structure in Figure 8 and observed residual gravity profiles taken in a direction N. 24° E.

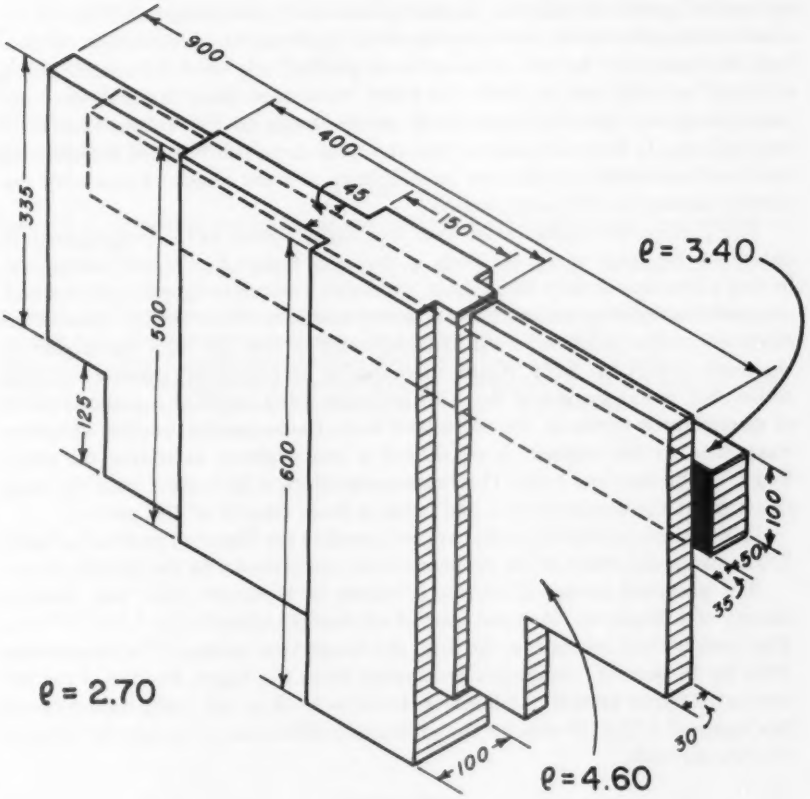


FIG. 8. Sketch showing proposed mass distribution causing the gravitational anomaly.

The anomalous density, or the difference in density between ore and country rock, was taken as 1.90 gm/cc. In view of the large number of density samples tested, this figure was considered to be representative of a good average. As a result, it was kept constant throughout the calculations.

It was necessary, however, to make many changes and adjustments in the

size and shape of the different segments. Several combinations of three-dimensional rectangular blocks were attempted. In each case the gravitational attraction was calculated for five cross-sectional profiles, one over the central point, and two on each side at 200-ft intervals. Note that these sections were not taken along the traverses, but rather perpendicular to the assumed strike of the ore body. It became apparent that the "end correction" factor, for applying the two-dimensional calculations to structures of finite length, was a very important element in the computations.

The geometrical configuration that was finally chosen as the best approximination to the shape of the ore body is shown in Figure 8. The main structure, having a constant density throughout, produced a calculated gravity effect which compared reasonably well with the observed anomaly. Nevertheless, most of the observed profiles exhibited a marked assymetry in that the force was higher on the north side of the body. Again, there can be no completely definite interpretation, but it was suspected that this behavior was a result of a preponderance of disseminated pyrite in the north wall rock. Consequently, another structure was added to the original. It consists of a long segment extending the entire length of the main ore body. This rectangular block is in contact with the main structure at the center section, and it has a mean density of 3.40 gm/cc.

The revised calculated profiles are compared to the observed profiles in Figure 7. The computed effect of the proposed structure is shown by the dotted curves.

The proposed configuration has a volume of 19.4×10^6 cubic feet. Using a density of 4.60 gm/cc., the total mass of ore was calculated to be 2.74×10^6 tons. This computation serves as a check on the integration method. The two answers differ by 14 percent, the integration answer being the larger, because of the disseminated pyrite present. Addition of the extra block to the configuration results in a figure of 3.21×10^6 tons for the mass and a difference of 0.6 percent between the two methods.

CONCLUSIONS

The shallow depth of the ore body plus the sharp density contrast between the ore and the country rock provide a very favorable situation for gravity prospecting. This deposit can be considered to be more or less typical of those in the Canadian Shield area. These facts suggest that gravitational prospecting should be a method of great importance in this area. A gravitational anomaly coinciding with an electromagnetic anomaly constitutes a powerful method of locating sulphide bodies.

Seldom, however, can an ore body be unequivocally detected and interpreted as such on the grounds of geophysical data. Most mining geophysical work is indirect. It traces formations or conditions whose relationship to possible ore locations can be deduced geologically.

Gravitational exploration in the petroleum field follows production line trends, whereas in mining applications it can be compared to the work of the hand craftsman. Nevertheless, hand craft turns out some of the finest products.

ACKNOWLEDGEMENTS

The writer wishes to express his appreciation to Rio Canadian Exploration Ltd. for permission to carry out this survey and for the use of their instruments. He wishes to thank Mr. H. A. Winkler, Mr. C. W. Pegg, Dr. H. O. Seigel, and Dr. F. S. Grant for their suggestions and advice in the preparation of this essay. Thanks are also due to G. R. Clark, L. H. Daly, and N. A. Dresner for their assistance in the field work.

REFERENCES

Brant, A. A., 1948, Some limiting factors and problems of mining geophysics: Geophysics, v. 13, pp. 556–581.

Dobrin, M. B., 1952, Introduction to geophysical prospecting: New York, McGraw-Hill Book Co., Inc.

Hammer, S., 1939, Terrain corrections for gravimeter stations: Geophysics, v. 4, p. 184–194.

Jakosky, J. J., 1950, Exploration geophysics: Los Angeles, Trija Publishing Co.

Kellog, O. D., 1929, Foundations of potential theory: New York, Frederick Ungar.

Nettleton, L. L., 1940, Geophysical prospecting for oil: New York, McGraw-Hill Book Co., Inc.

———, 1942, Gravity and magnetic calculations: Geophysics, v. 7, p. 293–310.

11TH ANNUAL MIDWESTERN EXPLORATION MEETING

OPENING ADDRESS

FRANK SEARCY, President, Geophysical Society of Tulsa

On behalf of the Geophysical Society of Tulsa, the Tulsa Geological Society, and the City of Tulsa, it is my privilege to welcome you to this, the Eleventh Annual Midwestern Exploration meeting. I think it is proper at this time to direct particular attention to the name of this meeting. It is not a geological meeting or a geophysical assembly; it is a gathering of exploration men jointly sponsored by geophysicists and geologists. This joint sponsorship is not merely a locally conceived idea. Resolutions passed by the Executive Committees of the SEG and AAPG have stated the existence of increasing need for mutual co-operation and co-ordination of scientific effort among geologists and geophysicists. It was further resolved that local sections and regional groups be encouraged to hold joint meetings that would not only continue but amplify this spirit of co-operation and co-ordination existing between these groups. Tremendous progress has been made since the day when non-co-operation was accepted as the standard relation between geologists and geophysicists. Geologists at that time looked upon the "doodle-bugger" as a not-too-necessary evil who would soon be properly disposed of. Certainly there was no possibility that the mysterious gadgets used by this "doodle-bugger" could ever contribute any information of such consequence that he would some day be welcomed as a member of the exploration team. On the other hand, the geophysicist, with unlimited taith in his scientific gadgets, failed to see that his information was useless until its geological significance was fully understood and appraised. He was not about to seek the help of such an out-of-date character as a "rock-hound" in making this appraisal. Unfortunately, in these early days management also was frequently at fault through its failure to realize that the best interpretation of a project was not several independent ones, but the one which made use of all possible bits of data fitted together to form the complete picture.

Out of all this early confusion there has come gradual evolution of a new species which can quite logically be labelled "explorationist." This "explorationist" fully comprehends that electric logs, sample logs, and cores which are the subsurface tools of the geologist are all closely related to gravity information, seismic record sections, magnetic data, and velocity logs—the tools of the geophysicist. The present day technique which combines electric logs, subsurface geology, and seismic data to produce a true geo-seismic section is but one indication of the progressively closer integration of geological and geophysical efforts. These geo-seismic sections permit the "explorationist" to analyze results quickly and are the means of presenting more factual information to management. This combination of geophysical and geological effort not only exists now in the upper levels but is definitely present at the grassroots. A modern exploratory group is, in many companies, comprised of three members—the geophysicist, the geologist, and the land man—working together as a team. A geophysical field crew is in continual close contact with the other members of the team. This assures that the crew is constantly advised regarding developments of drilling wells, new land plays in the area of interest, and any other data which may be pertinent to effective working of the project.

The program for this meeting has been tailored to foster the concept of complete coordination of effort in the entire exploration group. General Chairman, W. M. Erdahl, with General Co-Chairman James L. Martin, have assembled for their committee chairmen a group which is about equally divided as regards "doodle-buggers" and "rock-hounds." On behalf of the members of the sponsoring societies and the participating societies, I take this opportunity to express appreciation to all committee members for their excellent work.

The technical program arranged by Paul Lyons and his group is widely varied; it covers the entire exploration field. There are general interest papers on the various branches of geophysics: magnetics, gravity, and seismic; papers discussing geology of the Mid-Continent and other areas; and important papers bearing on the economic aspects of exploration. We will have the pleasure of hearing first-hand reports regarding IGY activity in Antartica and discussion of the IGY program as related to gravity and seismology. For the equipment design engineer in the laboratory there will be information concerning developments in magnetic recording; for the interpreter there will be

coverage of a wide range of subjects; and for the researcher, model studies, synthesized seismograms, and electronic computer programming.

It is our sincere hope that all of you will benefit from the technical program and that visits with your colleagues in the industry will be enjoyable. Again—welcome to Tulsa!

ABSTRACTS OF PAPERS PRESENTED AT THE ELEVENTH MIDWESTERN EXPLORATION MEETING

Tulsa, Oklahoma, April 17 & 18, 1958

Scale in exploration

O. C. CLIFFORD, JR.

"Scale" must be chosen with respect to the exploratory problem. When the derivation of the solution involves data of different units, a common and compatible unit must be found. This is as true of scale for economic problems in petroleum exploration as it is for technical problems. Examples from each field are given to show that the correct choice of scale will aid in the analysis of either problem.

Exploration in Guatemala

GEORGE S. BUCHANAN

No abstract of Mr. Buchanan's paper was given.

International Geophysical Year in Antarctica

REV. DANIEL LINEHAN, S.J.

No abstract of Fr. Linehan's paper was given.

International Geophysical Year program in gravity and seismology

GEORGE P. WOOLLARD

Gravity and seismological measurements constitute two of the eight disciplines being studied in connection with the International Geophysical Year. While lacking the glamour of outerspace studies, the widespread scientific ramifications of these measurements make them two of the more important phases of the IGY program. Briefly, the gravity measurements in terms of their ultimate use can be divided into: (1) standardization measurements using pendulums to establish an international gravity unit, (2) geodetic control measurements using both pendulums and high range gravimeters to establish an international network of base points, (3) geoidal studies based on world-wide gravity data taken on a regional basis over both the continents and oceans, (4) crustal structure studies based on regional gravity data, (5) crustal rigidity studies based on the crustal response to earth tide forces as measured with continuous recording gravimeters having a sensitivity of one microgal, (6) glaciological studies both as to thickness of ice, secular movement, accretion and wastage as deduced from gravimeter measurements, and (7) ocean tide and swell measurements as well as bathymetry as deduced from gravimeter measurements on floating sea ice.

Concurrently with these official IGY gravity studies, and related to them, are measurements for the determination of absolute gravity, the gravity gradient both in manned balloons up to 80,000 ft and in bathyscape down to oceanic depths. Observations of secular variations in gravity in areas of isostatic uplift that were depressed during Pleistocene glaciation. Evaluation of the orthometric correction to leveling through gravity measurements along traverses at the ground surface and at depth beneath the ground surface.

In seismology the IGY studies can be divided into: (1) fundamental studies of the earth's interior and energy transmission from earthquakes as revealed by data from new seismological observatories located to give better overall global coverage of the antipodal areas to those of marked earthquake activity of the related shadow zone belts, (2) special long period seismograph illustrations for the study of Lg and Rayleigh waves, (3) studies of Rayleigh wave phase dispersion and its relation to crustal structure, (4) studies of microseismic activity and its relation to other phenomena, particularly meteorology, (5) strain seismometer installations for the study of the rate of strain development in

seismic areas, and (6) explosive blast studies for the study of: (a) crustal structure and near surface geology, (b) the thickness of ice in glacial areas, (c) sound transmission within the oceans, and (d) the determination of the bathymetry, configuration beneath areas covered by sea ice.

A report on the status of some of the work outlined above is given along with some of the preliminary results obtained.

Para and diamagnetic susceptibilities in unvarying weak fields

WILLIAM SCHRIEVER

The diamagnetic susceptibilities of three pure metals and the paramagnetic susceptibilities of three salts in powder form, were measured with a coulomb-type torsion balance apparatus which had a force sensitivity of 10^{-6} dyne per division deflection. The field strengths were 2.5, 5 and 10 oersteds per the diamagnetic and 2, 3 and 5 oersteds per the paramagnetic substances. In all cases the susceptibilities decreased as the field strength increased.

Exploration program results in Kansas

EDWARD A. KOESTER

Darby Petroleum Corporation, a relatively small independent company, in 1935–36 conducted a reconnaissance seismic program on a part of the Central Kansas Uplift which was believed to have favorable chances for production. About 633,600 acres were covered by mile control in 36 townships in Ellis and adjoining counties. The marker used was a relatively shallow Permian anhydrite known as the Stone Coral anhydrite. The program cost less than $100,000.00 or about 15¢ per acre. As a result of this work, the company was able to secure acreage in many favorable spots through the years, although at the time the program was commenced the area was about 75 percent under lease. At least 14 oil discoveries may be attributed to this work. Most of the production has been secured from the Arbuckle dolomite, but profitable reserves have been found also in Lansing-Kansas City limestone of Pennsylvanian age. The properties developed as a result of this work had produced over 26,000,000 barrels of oil up to October 1, 1957, and were currently producing about 6,400 barrels per day. Ultimate reserves are estimated at 50,000,000 barrels.

So now you have it on tape

JOHN W. DALY

A discussion of magnetic tape recording by one who is not completely enchanted by the blandishments of salesmen.

A worm's-eye view of education

HUGHES M. ZENOR

Increased value must be attached to intellectual excellence, and a higher regard must be given to true knowledge and its applications, if the free world is to maintain its economic and political leadership. The growing complexity of scientific applications and the ever changing public relations of scientists require not only more intensive specialization in specific fields but also a continuous post university training program.

The heart of our educational system, the teachers and the professors, are its forgotten men; they are as a rule given negligible consideration. Any increases in the numbers and quality of our scientists and engineers must begin with the strengthening and encouragment of our faculties.

Seismic prospecting for oil—some facts, fantasies and economics

HUGH M. THRALLS

Much has been said publicly and privately regarding the need for co-ordination of geology and geophysics. One critical point has been ignored in most discussions; i.e., that neither the geologist

nor the geophysicist know the exact capabilities and limitations of the tool being used. Without this knowledge, facts and fancy become confused and lead to errors on the part of both. Errors by the exploration team invariably result in heavy expense.

The paper attempts to tabulate and illustrate a few of the limitations, capabilities, and potential capabilities of the seismic method.

Fracture types and distribution in the Appalachians

RAYMOND E. METTER AND ROBERT M. MITCHUM, JR.

Knowledge of the causes of natural rock fractures and of the distribution of various fracture types in different geologic environments is important to several phases of the oil industry. Fractures characteristic of compressional tectonics are present in the central Appalachian folded belt. These include conjugate *en echelon* fractures, shear fractures, rock cleavage, and gash fractures. Well developed patterns of regional joints are also present. These apparently started to form before major folding occurred.

Seismic reflections from within the pre-Cambrian basement complex, Oklahoma

M. B. WIDESS AND G. L. TAYLOR

Reflections from basement rocks of pre-Cambrian age were recorded in Comanche County, Southwestern Oklahoma, in the vicinity of the Wichita Mountains. The reflections, of good quality and extended continuity, provide a section in excess of 80,000 ft of igneous rocks that appears like a seismic section of sedimentary formations.

A well in the area drilled over 4000 ft of this pre-Cambrian section, encountering alternating layers of different types of igneous rocks exhibiting high contrasts in density. The material involved comprises primarily silicic rocks (granophyres, porphyritic rhyolites, rhyolite) and gabbroic rocks (diabase, gabbro, and basalts). Pre-Cambrian outcrops of much of the Wichita Mountains display sheet-like gently dipping layers, some of which persist for several miles. The seismic reflections are thus produced by the igneous layers of differential acoustic properties. An abrupt change of direction of dip occurring at mid-depth of the seismic section precludes the possibility that the seismic events are multiple reflections.

A simple method for determining the depth of shallow salt domes by refraction shooting

PAUL C. REED

This paper presents in very simple terms a procedure whereby refraction seismograph may be used to determine the depth to the top of shallow salt domes. The various steps necessary to obtain and compute the data are described and diagrammed in a manner such that the party chief, seismologist, or computer is able to lay out the program, reduce the data, and arrive at a straightforward interpretation and solution. The paper is virtually non-technical, and, because of its simplicity, the author believes that geophysicists and exploration groups operating in the sale dome provinces will find it helpful.

Generation of seismic waves by weight drops

S. N. DOMENICO

A series of experiments, designed to evaluate the weight-drop technique, was conducted in West Texas. These tests demonstrated the general nature of the seismic waves generated by a weight drop and the effectiveness of compositing drops in providing useful reflection information.

At the first of two test sites, discrete waves from single drops consisted of a refracted wave, an air-earth coupled wave, reflected wave segments, and fragmentary waves which are likely dispersive surface waves. A 72-seismometer array provided appreciably more reflected wave segments on records from single drops and also on records from the composite of these drops than did a single seismometer. Additional testing revealed that records prepared from weight drops along three parallel lines 100 ft

apart recorded at the same seismometer station are appreciably different. Compositing of the drop lines in general did not provide reflections superior to those on individual lines.

At the second test site, record quality appeared significantly superior to that at the first site. Discrete waves on records from single drops recorded by a 36-seismometer array were of the same types as those observed previously. The air-earth coupled wave, however, prominently developed at the first site, did not appear. Compositing of drops provided two prominent reflections which were correlatable over a 5-mile traverse.

An empirical velocity determination in Southwestern Oklahoma

DONALD R. OKSA

Lack of adequate velocity data can sometimes be overcome by the proper co-ordination of seismic and geologic factors. The basic assumption that seismic and geologic data are directly correlatable must be utilized to its fullest extent. Upon this basis reliable basic seismic data of time and delta t values are computed with variations in the other parameters to make the computed seismic data closely match the known geologic conditions by one of several standard computing methods. The empirical fitting of the seismic data to match geologic conditions established the velocity gradient which can then be extrapolated into immediately adjacent areas. An iso-velocity section can also be prepared, if it is desired. It generally appears that iso-velocity contours parallel formational strikes. The application of such empirically derived velocity data will result in seismic structural maps and cross-sections which are compatible with actual geologic conditions. The value of the oftentimes neglected true dip section is shown and is actually an integral part of the analysis. The application of electronic computing techniques makes such determinations much more rapid and makes the method entirely feasible.

The electroseismic effect

S. T. MARTNER AND N. R. SPARKS

The electroseismic effect manifests itself as an electrical potential generated in the subsurface by the passage of seismic waves. It can be detected at the surface of the ground with electrode pairs. The time of occurrence of the voltage clearly distinguishes the effect from either the ionization potential produced at the time of explosion or the seismic electric effect produced coincident with the arrival of seismic waves at the surface of the ground.

Evidence is presented which associates the electroseismic effect with the base of the weathered layer and demonstrates its characteristics in several areas and at various distances from the shotpoint. Its immediate utility appears to be the determination of the travel time through the weathering at the shotpoint.

A new migration plotter

J. A. HALL

A new mechanical migration plotter has been developed which accurately and rapidly migrates reflections and partial reflections. A carriage beneath a light table focuses a light line on the record or record section. When this light is aligned with the reflection the dip arm on the top of the table is in the migrated position. The migrated position is plotted by use of polar coordinates using the time (T) or depth (D) as the radius vector and t or a as the radius angle. The interpreter can then see his reflections in migrated position as he marks his record section. The machine is best adapted for use with record sections or depth sections but can be used with single records.

Present uses of the greater dynamic range of magnetic recording

FRED A. BROCK

In addition to the facility for recording wider frequency bands, the magnetic medium permits recording of greater contrasts in signal amplitudes. This may be utilized to improve event correlation with amplitude contrast removed to the degree desired on playback.

The Simpson group of Grayson County, Texas

HERBERT H. BRADFIELD

The Simpson Group in Grayson County consists, in descending order, of four formations: Bromide, 400–500 ft, green shale; McLish, 400–500 ft, about evenly divided limestone and shale; Oil Creek, 800–1000 ft, 200 ft of limestone at top, middle 450–600 ft of shale, 150–200 ft of limestone and sandstone at base; Joins, 160–240 ft of limestone. The latter rests on dolomite assigned to Ellenburger (L. Ord.). In thickness the Simpson ranges from a known maximum of about 2500 ft in the Gordonville trough where it is overlain with Viola limestone, to zero at the up-dip truncated edge on the flank of the Muenster arch.

The extensive and often complex faulting associated with the geologic history of Grayson County may be ascribed to *four* periods of movement.

The first of these movements, with the subsequent erosion, accounted for the amount and distribution of the Simpson. The last three affected the structural relationship of both Ordovician and Pennsylvanian, and they are vital to correct mapping by both geologist and geophysicist.

Only one Simpson horizon, the basal Oil Creek sand, a blanket-type deposit, has produced commercially in Grayson County. Sandusky, McMillan, and Webb Oil Creek sand fields, closely related, constitute the most important producing area, since they have up to 70 ft of good sand present. These pools, discovered in 1950–51, have produced approximately 7,000,000 barrels of oil. Whitesboro is the only other oil producing reservoir of consequence in the Oil Creek sand. This is a stratigraphic trap type accumulation at the up-dip truncated edge of the sand. Big Mineral and Sherman are essentially gas-condensate reservoirs. The latter is of considerable size, but it is undeveloped for economic reasons.

Geometrical factors of Sonic logging

F. P. KOKESH AND R. B. BLIZARD

The purpose of the Sonic log is to give a measure of formation velocity, but various geometrical factors can cause apparent velocity readings which are substantially different from the true velocity at the depth of measurement. An understanding of at least the most readily perceptible of these factors will enable one to derive greater value from the log. Bed thickness, hole size, caves, alteration of the formation adjacent to the bore, spacing of the receivers, and whether the tool is centered in the bore, are among the factors having an influence on the log. Centering the tool can increase the signal strength, but in large holes and slow formations the first arrival may come through the mud. The transmitter-receiver spacing which is needed to avoid this is given for various holes sizes and formation velocities. The effect of caves is shown with theoretical and actual curves. There is some evidence that action of the mud or stress concentration around the bore can change the velocity of the formation; the effect on the indicated velocity will be shown as a function of receiver spacing and of degree of depth of change.

Reflection time and structure—the forward and backward conversion illustrating multiple time branches

JOHN BEMROSE

A technique is illustrated to obtain the coordinates of points on the envelope of a series of wave fronts which permits the conversion of seismic time profiles to migrated depth profiles through the use of a linear increase in velocity with depth. The method is especially applicable to record sections. The technique is extended to the conversion of a time contour map to the corresponding migrated depth contour map. The converse method is also demonstrated; that is, the conversion of depth profiles to time profiles and depth contours to time contours to illustrate the possibility of the development of multiple time branches which are obtainable from certain structural configurations.

Correlation of adjacent gravimeter surveys

V. L. JONES

Gravity surveys conducted on adjacent areas at different times, by different personnel and with different gravimeters, often result in the two surveys not correlating properly at their common

boundary. If the calibration for one instrument is incorrect and the data obtained with this instrument are computed by using this calibration, the resulting contours are severely distorted along the common boundary of the two surveys. A correct meter factor may be computed for this gravimeter by extrapolating several profiles from the adjacent survey, made with a correctly calibrated meter, into the area surveyed with meter of faulty calibration. This may be accomplished by means of an extrapolation formula derived by the author. A least-squares method for calculating the correct meter factor is presented. The gravity values computed with this corrected factor will contour smoothly across the common boundary.

Resolution of anomalous mass

E. V. McCollum

Anomalous mass as computed at a point on the earth's surface may be defined by the formula:

$$m(R) = \frac{1}{2\pi G} \int_0^{2\pi} \int_0^R \{g(r, \alpha) - \bar{g}(R)\} r \, dr \, d\alpha$$

where $g(r, \alpha)$ is Bouguer Gravity, $\bar{g}(R)$ is the average value of gravity obtained on the circle with radius R, and G is the gravitational constant. Repeated calculations at a series of gravity stations (or arbitrary grid points) lead to values, when contoured, that tend to separate local gravity anomalies from neighboring anomalies. Regional effects are also subdued.

In favorable situations the causative mass may be approximated. In less favorable cases the anomalous mass aids in placing depth ranges on the disturbing mass.

A gravity simulator

Hughes M. Zenor

An apparatus is described, employing solid angles, whereby synthetic gravity maps may be readily obtained from assumed subsurface models of various degrees of complexity. Assumptions may be changed until a precise match is obtained with observed gravity data.

The analysis of elevation factor data in gravity surveys

John Bible

This paper involves the study of elevation factors as applied especially to areas of variable surface density. Means of determining the elevation factor at scattered points throughout an area are discussed. Graphic tests are made for possible correlation between factor and horizontal distribution, elevation, thickness of the crust, and others. Correlation is also studied between elevation factors and the surface geology. Means are then discussed on the amalgamation of the various factors into a continuous composite coherent gravity map.

Photogeological mapping results in the Midcontinent

Louis Desjardins

The writer found that the Midcontinent, when he lived in Tulsa in the 30's and early 40's, was fine proving ground for perfecting photogeology to the point of precise surface mapping and structural contouring upon the three-dimensional stereo photos. An early example is shown, but three-dimensional techniques in those days were laborious and slow.

After an absence of about 15 years, the writer returns to Tulsa, and gets a fresh look at this old region. His new work, distributed in many counties in Arkansas and Oklahoma in particular, is not available for this paper, but it can be said that it reflects enormous advances in techniques, more geological accuracy, and much faster work. For example, minor beds within the Atoka formation, which near Muskogee are given such proper names as George Fork, Dirty Creek, and Webbers Falls, are individually recognized in Arkansas 100 miles east of the Oklahoma line, even though the thickness has increased several times.

To provide a few illustrations for this paper, the writer borrowed some scattered photos from the Oklahoma and Arkansas state geologists, in fact he let them make the selections of localities on the basis of any special stratigraphic or mapping problems for which they wanted help. The complete results on four single photos were prepared, one on Pope County, Arkansas, and others in Sequoyah, Creek, and Noble Counties, Oklahoma. The usefulness of the measured stratigraphic columns incidental to the work is pointed out, the local problems needing help were apparent enough, and the solutions were just so much photogeological routine.

Pennsylvanian stratigraphy of the Anadarko Basin

PAUL L. LYONS

The Pennsylvanian of the Anadarko Basin has had a varied stratigraphic history as a result of tectonic movements in the borderland areas. The basin is widespread in total extent, and the transitions of sedimentary facies have provided abundant stratigraphic traps in multiple horizons. Isopachs and history of the Springer, Morrow, Atoka, Des Moines, Missouri and Virgil series are presented. Pre-Pennsylvanian areal distributions of rocks are shown as well as gravity and residual gravity maps.

Geologic structure and hydrocarbon accumulation

CLYDE G.-STRACHAN

The occurrence of deformation in northwest-southeast and northeast-southwest directions in the earth's crust in many areas has been increasingly noted by geologists and geophysicists during the past few years. This deformation is expressed by fractures, faults, and folds, and all of these structural types are very often definitely associated with hydrocarbon reservoirs. The paper of which this is an abstract endeavors to develop the idea that these structural systems originated in the earliest stages of the formation of the earth's crust, that they have persisted in variable degree through the sedimentary history of the earth, and that through their effect on sea bottom topography they have exerted a controlling influence on the character of local marine sedimentation and growth of organisms. This being so, exploration methods based on such a structural pattern could be successful in the search for all types of oil and gas accumulations. In this exploration the gravity and magnetic methods, being those to which we generally look for trend indications, should be of much use.

It is recognized that there are structural features and trends, many of them huge, which do not lie in the directions discussed. It is believed that they are due to crustal movements which have originated after the northeast-southwest and northwest pattern was established. On the regional uplifts resulting from these later crustal movements erosion sometimes exposes rocks which exhibit the older pattern. The folding in the older structural pattern may be accentuated by these later movements.

The use of geophysics in the development department

PETER B. BIKE

The development, or exploitation, department has attained a significant and integral status in many oil companies. Development formerly directed by the exploration and production personnel has evolved into a separate department staffed by geologists specializing in this field.

A case history of the Encino Field, San Patricio County, Texas, is discussed to illustrate how both exploration and development geophysics were applied successfully to a geological concept in the discovery and development of an oil field.

After completion of the discovery well, normal development ensued to the No. 9 test which was a dry hole. Geophysical data, previously obtained, was integrated into the then known complexities of the subsurface with additional success. A continuous re-evaluation of both subsurface and geophysical data was made. Subsequent seismic development program was conducted, and the data were again composited.

The results indicate the value of and need for geophysical personnel with geological experience in the development department.

Qualitative analysis of multiple reflections

W. S. HAWES

Seismic records from southern Alabama exhibiting strong multiple reflections are presented together with auxiliary data designed to yield a qualitative analysis of the specific case. In this conjunction several aspects of the general problem of multiple reflections are considered: surface and subsurface factors conducive to generation of high level multiples, the compounding effect of two or more strong reflectors, and methods for detection of multiples.

The electronic computer: a new tool for today's seismic interpreter

FRANK P. TROSETH

The electronic computers available today provide geologists and geophysicists with a new tool for finding oil. The ability of these machines to process a large amount of data accurately and speedily makes them particularly helpful to the seismic interpreter. By recording well formation tops, well velocity survey data, seismic reflection times, and other basic geological and geophysical information, an interpreter can obtain a wealth of information to aid him in his search for oil. Using the supplied information, an electronic computer can provide the interpreter with subsea depths, corrected reflection times, average velocities, interval thicknesses, or any other values which can be derived from the supplied information. The output data from a computer can be printed mechanically in the form of a table, graph, or map.

The examination of interval zones will probably be one of the most profitable activities made available to an interpreter who uses an electronic computer. Isopach information which has previously been available only after many hours of computation and drafting can now be requested almost at will. This means that the interpreter will be able to study many intervals investigating changes in velocity, wave travel time, and thickness. Studies of this type will certainly aid in the delineation of both stratigraphic and structural traps.

A synthetic study of effects of changing bed thickness on reflection seismograms

R. A. PETERSON

The effect of changes in the thickness of a single rock layer having a velocity lower than overlying and underlying rocks in a well column is studied by preparing a suite of synthetic seismograms. It is shown that within certain limits changes in bed thickness may be expected to be expressed in corresponding changes in reflection pulse width on the seismogram. However, a rather detailed knowledge of seismic pulse shape and recording instrument characteristics is necessary to determine these limits.

Seismic model experiments with shear waves

J. F. EVANS

The theory and technique of seismic model work are reviewed. The seismic waves employed in reflection prospecting are compressional waves; it is with such waves that most published seismic model research has been concerned. An elastic solid, such as the earth's crust, also transmits waves of deformation, commonly called shear waves. Experimentation with artificial shear waves in the earth has been limited by the difficulty of producing them in sufficient strength. On the other hand, small piezoelectric transducers for producing and detecting ultrasonic shear waves are now available, and it is thus made feasible to conduct experimental studies of shear waves in small-scale seismic models.

In the seismic model experiment described, it is demonstrated that shear waves having particle motion parallel to the surface (SH-waves) can be produced by applying an impulsive force to a point at or just below the surface of the solid. The line of action of this force must be parallel to the surface.

It is shown that SH-waves are reflected from the bottom of a single block only as SH-waves without transformation into other types of waves. By contrast, a compressional wave record taken on the same block is complicated by the presence of shear events which result from the transformation of compressional waves at the reflecting boundary. Finally, it is shown that the otherwise noise-free SH-wave reflection from the bottom of a single block is completely obscured by channeled surface shear waves (Love waves) when a thin layer is added to the model.

These results from model experiments with shear waves are in general agreement with the theoretical prediction.

Deep-hole geophone studies

F. K. LEVIN* AND R. D. LYNN

Seismic surveys have been made in eight widely separated wells with special wall-coupled geophones. These geophones accurately detected and reproduced elastic waves traveling in the earth.

Both direct (initial) pulses from shots and reflection events were studied. The complexity introduced into the initial pulses by secondary reflections varied greatly from well to well. Amplitude decayed as the negative 2.4 power of travel time. Pulse broadening caused by selective absorption of high frequencies was found. Different wells showed amounts of broadening ranging from nearly complete to little absorption of high seismic frequencies.

Reflections from beds below the geophone were traced to their origin in the earth. At two wells, the same reflections were found on surface seismograms, giving an identification of surface-detected reflections and reflector depth. Multiple reflections were distinguished from direct reflections and found to mask the latter at four wells. In one case, multiple reflections were identified with events on surface records.

Reflection coefficients found for direct reflections averaged 0.36.

Accurate velocity surveys of the wells resulted from this work. Travel times from continuous velocity logs of the wells agreed with survey times to ± 2 milliseconds.

* Paper presented by F. K. Levin.

ANNOUNCEMENTS

THE 28TH ANNUAL INTERNATIONAL MEETING

"Geophysical Frontiers—Today and Tomorrow" is the theme of the 28th Annual International Meeting of SEG which will be held in San Antonio on next October 13–16. To develop all phases of this considerable topic as completely as possible in such a short time, there will be sessions in mining, research, and instrumentation running concurrently with the general sessions.

MR. WELDON L. CRAWFORD, the General Chairman, has announced that in addition to SEG President O. C. CLIFFORD, JR., three other distinguished speakers have accepted the invitation to address the meeting: MR. FRED A. BARTLETT, Board Chairman of Socony Mobil Oil Company; MR. GEORGE S. BUCHANAN, President of AAPG; and SEÑOR ANTONIO J. BERMUDEZ of Petroleros Mexicanos.

The general schedule for the Meeting has been arranged as follows:

Sunday, October 12	Executive Committee Meeting and Registration
Monday, October 13	
Morning	General Session
Afternoon	General Session
	Mining Session
Tuesday, October 14	
Morning	General Session
	Mining Session
Afternoon	General Session
	Research Session

Wednesday, October 15	
Morning	General Session
	Research Session
Afternoon	General Session
	Research Session
Thursday, October 16	
Morning	General Session
	Instrumentation Session
Afternoon	General Session
	Instrumentation Session

The main features of the women's program are:

Monday, October 13	Walking tea along the San Antonio River and through La Villita
Tuesday, October 14	Luncheon at the Menger Hotel
Wednesday, October 15	
Morning	Brunch at one of the typical old homes of early San Antonio
Evening	Dance at the Seven Oaks Country Club

NEW GEOPHYSICAL JOURNAL

The Royal Astronomical Society of England has launched a new quarterly publication, the *Geophysical Journal*. It is to contain original papers, short notes and letters, and articles on the progress of geophysics, together with book reviews and reports of geophysical discussions. The Journal is edited by A. H. COOK and T. F. GASKELL in collaboration with R. A. LYTTLETON, the Geophysical Secretary of the Royal Astronomical Society.

The *Geophysical Supplement* to the *Monthly Notices* of the Royal Astronomical Society will be incorporated in the *Geophysical Journal*.

PUBLICATION OF INDEX TO SCIENTIFIC JOURNALS

GEOPHYSICS is among the 510 periodicals that are now being indexed by subject and author in a new publication which has recently been announced.

The primary subjects included in these indexes are solid state physics, nucleonics, radiation, optics, mechanics, astrophysics, radio, electronics, sound, astronomy, rockets, guided missiles, artificial satellites, and space travel. The indexes, which comprise several hundred thousand entries, have been compiled by the Library of the United States Naval Research Laboratory.

The original index cards are to be reproduced in book form by offset printing, 21 cards per page, 10 by 14 inches. Author and subject sections, and the monthly, quarterly, and annual supplements to each, can be purchased separately.

The publication will be available only to those who subscribe in advance of printing, which will begin in the third quarter of this year. It is offered by the Micro-Photography Company, 97 Oliver Street, Boston 10, Massachusetts.

NEW GEOPHYSICS CHAIR AT TULANE UNIVERSITY

To begin with the 1958–1959 Session, The Tulane University of New Orleans has announced the establishment of a Professorship of Geophysics in its Department of Geology.

DATA PROCESSING CENTERS FOR ANTARCTIC RESEARCH

The IGY Committee of the National Academy of Sciences has recently designated the University of Wisconsin and Ohio State University as centers where scientists returning from the Antarctic can process data obtained there during the U. S. International Geophysical Year program.

During the Antarctic winter, scientists will work at the two institutions on the material they gathered while in the field. The next group going to the Antarctic will use the universities' facilities in the same way when they return.

The Arctic Institute of North America recruits the personnel for IGY studies on the Antarctic ice sheet.

LATEST NUCLEAR RESEARCH IN PETROLEUM AVAILABLE

The latest research in the application of atomic energy to the petroleum industry will be presented at the 1958 International Conference on the Peaceful Uses of Atomic Energy to be held in Geneva next September 1–13.

The Document Service of The Chronicle of the United Nations Activities has inaugurated a complete service to supply the petroleum industry with materials of the Conference. The lists of papers to be presented are now available, and these include several hundred contributions dealing with petroleum research from the major laboratories throughout the world.

Some of the topics which the Conference will undertake to cover are the technical and economic aspects of nuclear power plants; the use of nuclear power for marine propulsion; new information on fuel cycles, with emphasis on operational problems and economic implications; and the geology of raw material supplies, with special emphasis on new methods and instruments for prospecting and exploration.

These lists may be obtained free of charge by writing to:

Petroleum Document Service
The Chronicle of United Nations Activities
234 West 26th Street
New York 1, New York

PERSONAL ITEMS

At its 43rd Annual Meeting in Los Angeles last March, the American Association of Petroleum Geologists conferred its Sidney Powers Memorial Medal on MR. PAUL WEAVER. Mr. Weaver was the President of SEG in 1932–1933, the President of AAPG in 1948, and the Vice-President of the Texas Academy of Sciences in 1946.

The John Fleming Medal of the American Institute of Geonomy and Natural Resources was presented on last May 14 to DR. and MRS. J. B. HERSEY in the presence of their friends and colleagues at the Woods Hole Oceanographic Institution. The award was presented "for outstanding accomplishment in science and human welfare" on the recommendation of the Institute's Board of Directors and 67 foreign correspondents representing 26 countries.

The Atlantic Refining Company has announced the appointment of SEG President O. C. CLIFFORD, JR., to the newly created position of Manager of the foreign crude oil exploration division. He was formerly Chief Geophysicist in the Company's domestic exploration division. MR. C. H. HIGHTOWER, who has been serving as Assistant Chief Geophysicist since 1949 will succeed Mr. Clifford in his former position.

The United Geophysical Corporation announced the following changes in its officers and directorate after its annual meeting last March in Pasadena. On March 31, 1958, MR. C. C. LISTER, President of the Corporation since 1953, retired as an Officer and Director. MR. E. A. PIELEMEIER was elected Chairman of the Board and MR. BART W. SORGE the President of the United Geophysical Companies. MR. R. G. SOHLBERG was elected President of United ElectroDynamics, Inc. Re-elected as Vice-Presidents and Directors of the Corporation were MR. L. A. MARTIN, DR. R. A. PETERSON, and MR. R. G. SOHLBERG. MR. M. G. NOBLE was re-elected Secretary-Treasurer and Director, and MR. F. H. AGEE was added to the directorate to fill the vacancy caused by Mr. Lister's resignation.

Announcement was made last April of the promotions of J. R. BLAISDELL to Assistant Vice-President of the Seismograph Service Corporation and S. W. FRUEHLING to Vice-President of SSC (International). Mr. Fruehling is in Rio de Janeiro managing the firm's operations in Brazil, and Mr. Blaisdell is located at the offices in Tulsa where he is the Personnel Manager.

MR. KENNETH W. PAUL of Houston has recently been appointed the Manager of the Lease and Oil Properties Evaluation Department of the Mayflo Oil Company of Dallas.

The Petty Geophysical Engineering Company of San Antonio has announced the election of MR. DAVID F. TVER as Executive Vice-President and MR. W. HARRY MAYNE as Vice-President of Technical Services.

MR. FRANK P. SONNENBERG has been appointed Chief Geologist for Chaco Petroleum, S.A., the Bolivian subsidiary of the Tennessee Gas Transmission Company. His headquarters are in Cochabamba, Bolivia.

MR. MILLER QUARLES, JR., has moved with his wife and three daughters to Paris, France, where he is Consulting Geophysicist for the recently formed Compagnie Reynolds de Géophysique which is located at 13, Rue des Sablons, Paris 16e.

After the meeting of the Board of Directors of Texas Instruments Incorporated which was held last April 16, MR. EUGENE MCDERMOTT, Board Chairman since 1948, announced the election of two new officers. The Board elected a new Chairman, MR. J. E. JONSSON, and a new President, MR. PATRICK E. HAGGERTY. Mr. McDermott, a co-founder of the company, is continuing as an Officer and Director, and he was elected the Chairman of the Executive Committee. On last April 23, the Company announced the appointment of MR. RICHARD A. ARNETT as Marketing Manager of the Industrial Instrumentation Division.

MR. E. F. K. (RUDY) ZARUDZKI has resigned his position as Staff Seismologist with the United Geophysical Company of Canada and has joined the geophysical staff of the Pan American Petroleum Corporation. His address is:

Petroleum Building
310—9th Avenue, W.
Calgary, Alberta

MR. C. N. HURRY, The Carter Oil Company, Box 801, Tulsa 2, Oklahoma, has an extra set of GEOPHYSICS, v. 13 (1948)—22 (1957), which he is willing to sell at a reasonable price.

THREE MORE PAST PRESIDENTS OF SEG RECEIVE THEIR PLAQUES

In the upper picture, DEAN WALLING (left), President of the Pacific Coast Section of SEG, is shown presenting the presidential plaques to former SEG Presidents CURTIS H. JOHNSON (center) and JOHN J. JAKOSKY (right) at the meeting of the Pacific Section in Los Angeles on last February 13. Mr. Johnson was President of SEG in 1952–1953, and Dr. Jakosky in 1946–1947.

In the lower picture, GEORGE E. WAGONER (left), who served as President in 1950–1951, is shown receiving his plaque from SEG President O. C. CLIFFORD, JR.

CALENDAR OF MEETINGS

1958

September

6–8 Canadian Society of Exploration Geophysicists, Sixth Annual "Doodlebug" Golf Tournament, Banff Springs Hotel, Alberta (Robert A. Boulware, Chairman, 839 24th Avenue, S.E., Calgary, Alberta)

16–20 Kansas Geological Society, 22nd Field Conference, Trinidad, Colorado (Don B. Brown, Chairman)

October

13–16 Society of Exploration Geophysicists, 28th Annual International Meeting, Hotel Gunter, San Antonio (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

22–24 American Association of Petroleum Geologists, Southwest Regional Meeting, City Auditorium, Mineral Wells, Texas

November

6–7 American Association of Petroleum Geologists, Pacific Section Annual Meeting, Los Angeles

1959

February

15–19 American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., Annual Meeting, San Francisco

March

16–19 American Association of Petroleum Geologists—Society of Economic Paleontologists and Mineralogists, National Convention, Memorial Auditorium, Dallas

October

28–30 American Association of Petroleum Geologists, Mid-Continent Regional Meeting, Broadview Hotel, Wichita, Kansas

November

9–12 Society of Exploration Geophysicists, 29th Annual International Meeting, Biltmore Hotel, Los Angeles (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

1960

November

7–10 Society of Exploration Geophysicists, 30th Annual International Meeting, Moody Convention Center, Galveston (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

1961

November

5–9 Society of Exploration Geophysicists, 31st Annual International Meeting, Denver (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

1962

September

17–20 Society of Exploration Geophysicists, 32nd Annual International Meeting, Calgary, Alberta (Colin C. Campbell, Box 1536, Tulsa 1, Oklahoma)

* * * * *

July 1, 1957 to December 31, 1958

International Geophysical Year (Worldwide) *vide* GEOPHYSICS, v. 21, p. 257–259, and v. 21, p. 681–690 (H. Odishaw, National Academy of Sciences, Washington 25, D.C.)

PROFESSIONAL DIRECTORY

CALIFORNIA

H. WAYNE HOYLMAN
Consultant
Petroleum and Mining Exploration
Aerogeophysics Company — 816 W. 5th St.
Mutual 6428 — Los Angeles 17, Calif.

L. F. IVANHOE
Consulting Geologist and Geophysicist
Domestic and Foreign Exploration
Phone: FA 50283 — 2810 Elmwood Avenue
Cable: IVANHOE — BAKERSFIELD, CALIFORNIA

CURTIS H. JOHNSON
Consulting Geophysicist
412 WEST SIXTH ST. — LOS ANGELOS, CALIFORNIA

WILLIAM CROWE KELLOGG
Geological Engineer
Kellogg Exploration Company
Geologists — Geophysicists
Electrical — Magnetic — Gravity — Radioactivity
Air-Ground Surveys — Interpretation
3301 NORTH MARENGO — ALTADENA, CALIFORNIA

HENRY SALVATORI
Western Geophysical Company of America
1116 Pacific Mutual Bldg.
523 W. 6th Street
LOS ANGELES 14, CALIFORNIA

JOSHUA L. SOSKE
Geologist and Geophysicists
SCHOOL OF MINERAL SCIENCES
Stanford University
STANFORD, CALIFORNIA

CALIFORNIA

ELLIOTT SWEET
Gravity Meter Surveys
Gravity and Seismic Interpretation
SWEET GEOPHYSICAL CO.
21544 Rambla Vista Drive
MALIBU, CALIFORNIA

GEO. SHUMWAY
GEOLOGICAL DIVING CONSULTANTS, INC.
Underwater studies of bedrock and sediments
P.O. Box 6571 — San Diego 6, California

COLORADO

Milt Collum — Wes Morgan
PETROLEUM GEOPHYSICAL COMPANY
Contract Seismograph Crews
Seismic Review and Interpretations
Rocky Mountain Area
KEystone 4-0253
620 19th Street — Denver 2, Colorado

KANSAS

CHARLES C. (RUSTY) WILLIAMS
Geologist-Geophysicist
Williams Seismograph, Inc.
252 South Green Street
WICHITA, KANSAS

LOUISIANA

CARL L. BRYAN
Consulting Geophysicist-Geologist
804 Texas Eastern Bldg. — Telephone
SHREVEPORT, LA. — 5-1924

MISSISSIPPI

EWIN D. GABY
Delta Exploration Company
Jackson — Mississippi

MISSOURI

LEROY SCHARON
Mining and Engineering Geophysics
567 Brookhaven Court
Kirkwood 22 Phone
St. Louis, Missouri KIrkwood 1578-W

NEW YORK

ROLAND F. BEERS
ROLAND F. BEERS, INC.
Petroleum and Minerals Exploration Consultants
Ground and Airborne Surveys
Data Reduction and Analysis
P.O. Box 1019 Troy, New York
Ashley 2-6478; 2-2351

OKLAHOMA

THOMAS J. BEVAN
Geophysicist
914 American Airlines Bldg. Phone CHerry 2-7508
TULSA 3, OKLAHOMA

ARNOLD H. BLEYBERG
Petroleum Exploration Consultant
Domestic & Foreign Services
MID-AMERICA BANK BLDG.
OKLAHOMA CITY 2, OKLA. PH.: CENTRAL 2-0913

JULIAN M. BUSBY
Geological Engineer—Geophysicist
SPECIALIZING IN MAGNETICS
OKMULGEE, OKLAHOMA
529 COMMERCE BLDG. PHONE 2568

OPIE DIMMICK
Century Geophysical Corp.
Tulsa, Oklahoma Phone 5-7111

R. W. DUDLEY
Oil Exploration Consultant
Geologist *Geophysicist*
608 First National Bldg. Telephone FOrest 5-5255
OKLAHOMA CITY 2, OKLAHOMA

OKLAHOMA

CRAIG FERRIS
Geophysicist
E. V. McCollum & Co. GeoSeis, Inc.
515 Thompson Bldg.
TULSA 3, OKLA.

TOM D. MAYES
Mayes-Bevan Co.
Gravity Meter Surveys
and Interpretations
305 Kennedy Building
TULSA, OKLAHOMA

E. V. McCOLLUM
Geophysicist
E. V. McCollum & Co.
515 Thompson Building
TULSA, OKLAHOMA

GLENN M. McGUCKIN
Seismograph Consultant
Data Interpretation Current Supervision
SALES: McGUCKIN (Patented) SEISMOGRAPH
SECTION PLOTTER (DIP MIGRATOR)
23 Years Experience:
Supervising, Contracting, Consulting
Phone JEfferson 4-0853 1304 Ann Arbor
NORMAN, OKLA.

RICHARD A. POHLY
Gravity Surveys and Re-interpretation
POHLY EXPLORATION COMPANY
1135 E. 38th St. RIverside 2-2009
TULSA 5, OKLAHOMA

BEN F. RUMMERFIELD
Geologist and Geophysicist
CENTURY GEOPHYSICAL CORPORATION
503 Jenkins Building 1105 7th Ave., W.
Tulsa 3, Oklahoma Calgary, Alberta

JOHN J. RUPNIK
RUPNIK AND BALLOU
Petroleum Exploration Consultants
GEOPHYSICAL & GEOLOGICAL COORDINATION
1102 HUNT BLDG., TULSA 3, OKLAHOMA
LUther 7-2435

OKLAHOMA

HUGH M. THRALLS
Consulting Geophysicist
Box 9577 GIbson 7-3921
TULSA, OKLAHOMA

PENNSYLVANIA

W. B. AGOCS
Geophysical Consultant
Aero Service Corp.
236 E. Courtland
PHILADELPHIA 20, PENNSYLVANIA

TEXAS

JOHN F. ANDERSON
ANDERSON & COOKE
Oil Exploration Consultants
Geological Consulting
Seismic Surveys & Interpretations
665 San Jacinto Bldg. Houston 2, Texas

WALTER D. BAIRD
Consulting Geophysicist
NEIL P. ANDERSON BUILDING
PHONE EDison 6-8400 FORT WORTH 2, TEXAS

KEITH R. BEEMAN
Electronic Consultant
Seismograph and Allied Equipment
P.O. Box 13058
Houston, Texas

JOHN L. BIBLE
Southern Geophysical Company
Seismic—Gravity—Magnetics
3339 N. Rice Ave. Houston, Texas

HART BROWN
Brown Geophysical Company
Gravity-Meter-Surveys
Interpretations
5300 Brownway Rd. Houston 19, Texas

TEXAS

JOHN W. BYERS
Byers Exploration Company
Seismic, Gravity and Magnetic Surveys
709 M. & M. Building Phone
HOUSTON, TEXAS CApitol 4-2423

R. A. CRAIN
Texas Seismograph Company
Panhandle Building
WICHITA FALLS, TEXAS

PAUL D. CRAWFORD
Askania Magnetometer
Surveys
1421 Milam Bldg. San Antonio, Texas

R. H. DANA
Dana Explorations, Inc.
1301 W. T. Waggoner Bldg.
Fort Worth, Texas

PAUL FARREN
Geophysical Consultant
Specializing in Seismic Interpretation,
Review, and Supervision
1528 Bank of the Southwest
HOUSTON 2, TEXAS FA 3-1356

L. F. FISCHER
Exploration Consultant
Geophysicist
Geologist
621-A City National Bank Bldg. Houston, Texas

J. F. FREEL
RESEARCH EXPLORATIONS, INC.
5134 Westheimer Road
Houston, Texas

TEXAS

E. JOE SHIMEK — LLOYD PAITSON

GEOPHYSICAL ASSOCIATES

P.O. Box 6005 — Houston 6, Texas

Seismic

JOHN A. GILLIN

National Geophysical Company

8800 Lemmon Avenue

Dallas 9, Texas

IRVING M. GRIFFIN, JR.

Consultant in
Seismic Review and Interpretation
and
Field Crew Supervision

FAirfax 3-9111 — 1331 Esperson Bldg.
JAckson 2-4558 — Houston 2, Texas

T. I. HARKINS

Independent Exploration Company

1973 West Gray
P.O. Box 13237
Houston 19, Texas

J. G. HARRELL

Mid-Continent Geophysical Co.
Contract Seismograph Crews
Seismic-Reinterpretations

2509 West Berry — Fort Worth, Texas

SIDON HARRIS

Southern Geophysical Company

6640 Camp Bowie Blvd. — Fort Worth, Texas

J. O. HOARD

HOARD EXPLORATION COMPANY

Esperson Building — Houston, Texas

TEXAS

W. B. HOGG

Geophysical Consultant

1915 Adolphus Town Bldg.
DALLAS 1, TEXAS

LEO HORVITZ

Geochemical Prospecting

Horvitz Research Laboratories
3217 Milam Street
HOUSTON, TEXAS

JOHN S. IVY

Niels Esperson Building

HOUSTON, TEXAS

J. C. KARCHER

Geophysicist

Adolphus Tower
DALLAS, TEXAS

MARTIN C. KELSEY

Rayflex Exploration Company

6923 Snider Plaza — Dallas 5, Texas

H. KLAUS

Geologist and Geophysicist

Klaus Exploration Company
Gravimetric and Magnetic Surveys
and Interpretations

P.O. Box 1617 — Lubbock, Texas

PAUL H. LEDYARD

Mid-Continent Geophysical Co.

Contract Seismograph Crews
Seismic-Reinterpretations

2509 West Berry — Fort Worth, Texas

TEXAS

C. T. MacALLISTER
Geophysical Consultant
Seismic Interpretations and Field Supervision
6327 Vanderbilt, Houston 5, Texas
Telephone: MA 3-4181

HAYDON W. McDONNOLD
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

A. E. "SANDY" McKAY
Geologist and Geophysicist
Continental Geophysical Co.
FORT WORTH, TEXAS
2111 Continental Life Bldg. Phone EDison 2-9231

GEORGE D. MITCHELL, JR.
Geologist and Geophysicist
911 Mercantile Securities Bldg. Dallas, Texas

P. E. NARVARTE
Consulting Geophysicist
Seismic Interpretations
Current Supervision and Review
Frost National Bank Building
San Antonio, Texas

L. L. NETTLETON
Gravity Meter Exploration Co.
Interpretation of Gravity Surveys
Interpretation of Aeromagnetic Surveys
340 M. Esperson Bldg.
HOUSTON 2, TEXAS

W. W. (IKE) NEWTON
Geophysicist
823 Corrigan Tower
DALLAS, TEXAS

TEXAS

J. O. PARR, JR.
Consulting Geophysicist
Methods & Instrumentation
for
Seismic & Radiometric Surveys
202 Janis Rae San Antonio, Tex.

C. W. PAYNE
Payne & Warren
Geophysical Consultants
2210 Continental Life Bldg.
Fort Worth TEXAS

H. B. PEACOCK
Consulting Geophysicist
8400 Westchester
DALLAS 25, TEXAS

J. C. POLLARD
GEOPHYSICAL ENGINEERING
SEISMIC . . GRAVITY . . . MAGNETIC SURVEYS
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

ROBERT H. RAY
GEOPHYSICAL ENGINEERING
SEISMIC . . . GRAVITY . . . MAGNETIC SURVEYS
2500 Bolsover Rd., P.O. Box 6557, Houston 5, Tex.

SAM D. ROGERS
Rogers Geophysical Company
Rogers Explorations, Sociedad Anonima
3616 West Alabama Houston 6, Texas

C. WHITNEY SANDERS
Consulting
Petroleum Geologist-Geophysicist
U. S. and European Exploration
1132 Bank of the Southwest Building
HOUSTON 2, TEXAS

TEXAS

RAYMOND L. SARGENT
Magnetometer Surveys
Interpretations
M & M Bldg.
HOUSTON 2, TEXAS

SIDNEY SCHAFER AND COMPANY
Geophysicists and Geologists
EXPLORATION CONSULTANTS
Domestic and Foreign
Sidney Schafer — 2200 Welch Avenue
Jack C. Weyand — Houston 19, Texas

HUBERT L. SCHIFLETT
States Exploration Company
Seismic, Gravity and Magnetic Surveys
5313 Richmond Road — Highway 75 North
HOUSTON, TEXAS — SHERMAN, TEXAS

H. B. SMYRL
Portable Seismograph, Inc.
706 Frost National Bank Bldg.
San Antonio 5, Texas

NELSON C. STEENLAND
Gravity Meter Exploration Company
Geophysicist
340 Mellie Esperson Building — Houston, Texas

R. C. SWEET
Geophysicist
1111 Bering Dr. — Houston, Texas

R. MAURICE TRIPP
Oil and Mineral Exploration Research
3525 Beverly Drive — Dallas, Texas

TEXAS

F. RITCHIE WALLACE
Geophysical Consultant
701 Polk — Off. FAirfax 3-7719
Houston 2, Texas — Res. MOhawk 5-5542

KIRBY J. WARREN
Payne & Warren
Geophysical Consultants
2210 Continental Life Bldg.
Fort Worth — Texas

E. DARRELL WILLIAMS
Geophysicist
Specializing in Radiometric Exploration for Oil
3114 PRESCOTT ST., HOUSTON 25, TEXAS
PHONE MA 3-3991

JOHN H. WILSON
Exploration Consultant
1201 Sinclair Bldg.
FORT WORTH, TEXAS

CHARLES C. ZIMMERMAN
Geologist & Geophysicist
Keystone Exploration Company
2813 Westheimer Road
HOUSTON, TEXAS

WYOMING

Exploration Geology — Seismic Reviews
Evalutions — Seismic Supervision
JOHN F. PARTRIDGE, JR.
Consulting Geologist—Geophysicist
P.O. Box 258 — Room 211 O-S Building
Phones 2-6485 and 2-3328 CASPER, WYOMING

CANADA

R. E. DAVIS
Farney Exploration Company, Ltd.
830-8th Avenue West
CALGARY, Alberta, Canada

CANADA

JOHN O. GALLOWAY

Petroleum Consultant

627 8th Ave., W. Calgary, Alberta

THEODORE KOULOMZINE

Geologist & Geophysicist

Koulomzine, Geoffroy & Co.

P.O. Box 870

VAL D'OR Que. Canada.

LUNDBERG EXPLORATIONS LIMITED

Consulting Geologists and Geophysicists

Specialty—Airborne, Radiation, Electrical & Magnetic Surveys

96 Eglinton Avenue E.
Toronto 12, Canada

CANADA

D. BRUCE McDOUGALL

Geophysicist

201 Oil Exchange Bldg. Calgary, Canada

GEORGE W. SANDER

Consulting Geophysicist

174 Douglas Ave. N., Oakville, Ontario Phone VIctor 4-6345

DR. W. F. STACKLER

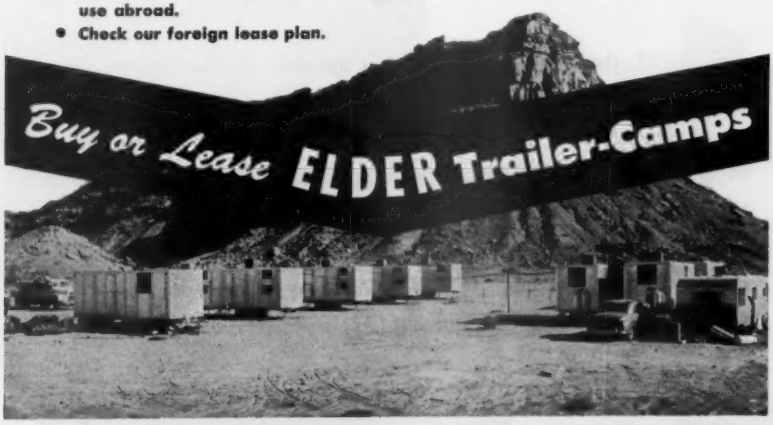
Consulting Geophysicist

Phone 447303
1937 25th Avenue S.W.
CALGARY, ALBERTA

- **TURNKEY OPERATION—includes trailers, personnel and supplies.**
- **Specialists in trailers built for use abroad.**
- **Check our foreign lease plan.**

Complete Trailer Camps

for your field crew. Kitchen trailers, diners, showers, offices, sleepers, power plants, water tank and gasoline trailers.



ELDER TRAILER and BODY, INC. 4830 Race · Denver, Colorado
Phone: AMherst 6-1781

For Better Seismograph Service

TEXAS SEISMOGRAPH CO.

PANHANDLE BLDG. WICHITA FALLS, TEXAS

Review of Scientific Instruments

•

Since 1923, the leading publication in the field of scientific instrumentation. Over, 1,000 pages annually of the latest original research material on new instruments for measurement and control. Written and edited by experts, the "Review" is the most widely quoted and referenced publication in its field. Indexed annually by subject. Circuits, computers, counters, electrical measurement, laboratory techniques, mechanics, microwaves, nuclear machines, vacuum techniques, X-Ray diffraction, many others. Over 88 subjects covered. Annually, 12 issues, $9.00. Single copy, $1.25

AMERICAN INSTITUTE OF PHYSICS

335 East 45 Street **New York 17, N.Y.**

There's a Kodak dealer *where you need him . . .*

Whether you're prospecting in Montana, Louisiana, or points between, you'll find a Kodak dealer located where it's most convenient for you.

These dealers are stocked to supply all your photo-recording needs. They offer *Kodak Linagraph 480 Paper,* the standard of the industry: gives you clean, sharp traces, takes written notations easily, can be processed at temperatures up to 120 F; *Kodak Linagraph 483 Paper:* with the same emulsion as 480 but on extra thin stock for more footage per roll; *Kodak Linagraph 809 Paper:* with strong ledger base and special undercoating for optimum trace clarity; *Kodak Linagraph 1350 Paper* (Dual Winding): lets you make two records at once; *Kodak Linagraph Chemicals:* for finest processing results.

Your Kodak dealer will be glad to help you choose the Linagraph Materials best suited to your needs.

The new booklet "Kodak Materials for Geophysical Exploration," gives you complete information on Kodak Linagraph Materials. It's available from your Kodak dealer.

EASTMAN KODAK COMPANY
Rochester 4, N. Y.

Kodak

OLSEN SEISMOGRAPH SUPPLIES

GROUNDHOG DRILL BITS

YOURS FOR FASTER AND CHEAPER FOOTAGE

GARLAND, TEXAS
BOX 428

PHONES
BROADWAY 6-5117
NITE BROADWAY 6-2808

INSTRUMENT FABRICATION

To Your Specifications for:

EXPLORATION EQUIPMENT
LOGGING EQUIPMENT

. . . by experienced craftsmen and fabrication engineers

CUSTOM FABRICATION CORPORATION

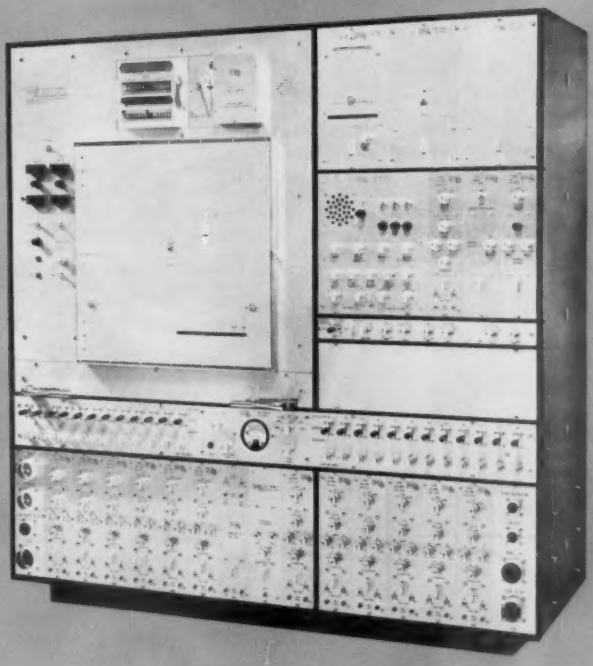
2711 Dawson Road — Tulsa, Oklahoma
P.O. Box 3391, Whittier Station — Madison 6-6716

Issued Feb. 1956
FIFTIETH ANNIVERSARY
Economic Geology
1905-1955
(in two parts)

This publication comprises some 24 review papers by specialists in their fields, on wide phases of economic geology, including ore deposits and ore genesis, sedimentary deposits of rare metals, uranium deposition, coal petrology, time of oil and gas accumulation, oxidation of copper sulphides and secondary sulphide enrichment, pegmatite deposits, carbonate mineralogy of limestones and dolomites, engineering geology, influence of geological factors on the engineering properties of sediments, geochemistry and geophysics in prospecting, hydrothermal deposits, metallogenetic epochs and provinces, mineral synthesis, geologic thermometry, developments in clay mineralogy and technology, temperature in and near intrusions, and other important topics of interest to the professions of geology, mining and engineering. All of the authors are specialists in their field, and present a critical and stimulating review of the literature.

Price to Subscribers (including members, non-member Journal subscribers, and students whether subscribers or not) $6.00
Price to Non-Subscribers to Journal 8.00

Order from: Economic Geology Publishing Company
105 Natural Resources Building
Urbana, Illinois



SIE MS-15 MAGNETIC-SEISMIC FIELD RECORDING SYSTEM...a completely unitized FM installation for use in any field location.

The MS-15 Magnetic-Seismic Field Recording System is a completely new and economical "one-package" unit for magnetic recording and monitoring in the field. All of the **high fidelity** advantages of the time proven frequency modulation method are obtained **at the same cost as AM instruments.** The unique "one-package" design of the MS-15 eliminates interconnecting cables, providing dependability characteristics so necessary in a field system.

Twenty-four broad-band, linear phase shift seismic amplifier-FM modulator combination channels are specifically designed for magnetic recording to take advantage of the inherent qualities of the famous **standard** SIE tapes. Bridged-T hi-line filters are available. The twenty-four seismic data channels and four information channels can be played back through an SIE GA-22 or GA-33 seismic amplifier sequentially and displayed on a monitor drum to verify record quality. Either pen or electro-stylus reproducing methods are available, and **no photographic developing processes are required. A dry** reproduction of the magnetic recording is available only 2½ minutes after the shot is fired. The system is housed in one sturdy unit and since no darkroom and developing facilities are required, the MS-15 is easily installed in a portable recording cab and transported in a small pickup truck or marsh vehicle.

In every characteristic—FM high-fidelity, dependability and ease of maintenance, operating convenience and flexibility, the MS-15 maintains the standards which have made SIE geophysical instrumentation "THE STANDARD OF THE INDUSTRY."

SOUTHWESTERN INDUSTRIAL ELECTRONICS CO.

P.O. Box 13058 2831 Post Oak Rd. Houston 19, Texas

SIE

In 1958
SIE GeoData
Processing Centers
are revealing
the world's complete
sub-surface picture

Today, all over the world, MS-12 GeoData Systems are in use. The world's leading petroleum and geophysical organizations are being equipped with **SIE GeoData Systems** as rapidly as possible. These outstanding companies have chosen GeoData equipment in order to utilize properly **all** of the seismic information acquired by modern magnetic recording methods. They have found the GeoData concept offers maximum interpretation flexibility while maintaining the highest standards of accuracy over wide variations in record quality.

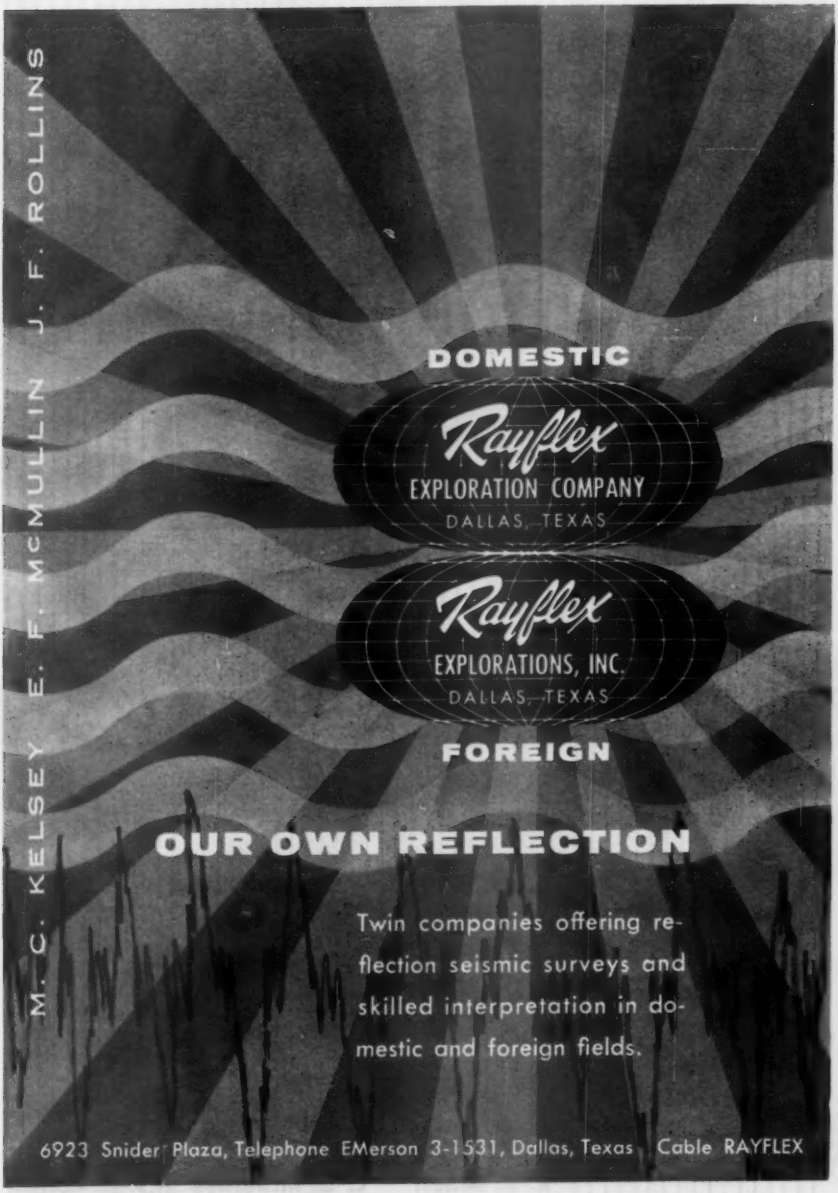
GeoData is the essential element required for **full utilization of geophysical data.** The wide acceptance of the MS-12 System demonstrates again how SIE instruments meet every industry requirement in every phase of the modern exploration program.

MS-12 GeoData Equipment with sequential processing reduces first cost — improves accuracy — simplifies operation — provides the complete sub-surface picture.

SIE

SOUTHWESTERN INDUSTRIAL ELECTRONICS COMPANY

2831 Post Oak Road • P. O. Box 13058 • Houston 19, Texas

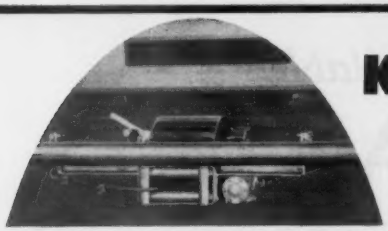

M. C. KELSEY E. F. McMULLIN J. F. ROLLINS
DOMESTIC
Rayflex
EXPLORATION COMPANY
DALLAS, TEXAS
Rayflex
EXPLORATIONS, INC.
DALLAS, TEXAS
FOREIGN
OUR OWN REFLECTION
Twin companies offering reflection seismic surveys and skilled interpretation in domestic and foreign fields.
6923 Snider Plaza, Telephone EMerson 3-1531, Dallas, Texas Cable RAYFLEX

Seismic Engineering COMPANY

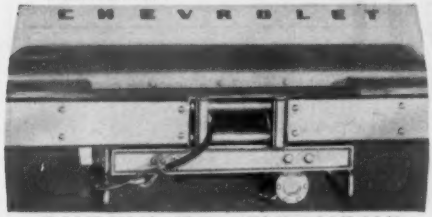
ENGINEERED SEISMIC SURVEYS

6111 MAPLE AVENUE • DALLAS • TEXAS

R. D. Arnett C. G. McBurney J. H. Pernell

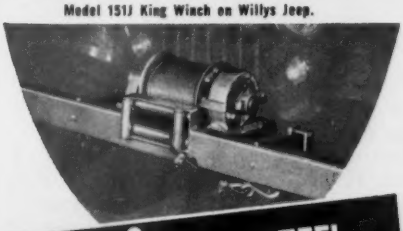


Model A-11 King Winch on A-120 (4x4) all-wheel-drive International truck.*



Model CD-8116 King Winch on 1958 Chevrolet Model 31 (4x4).

Model 151J King Winch on Willys Jeep.



KING WINCHES

. . . for Willys, International, Chevrolet, GMC, Ford, Land Rover and other vehicles

COMPLETE, READY-TO-INSTALL KING FRONT-MOUNT WINCH ASSEMBLIES FEATURE:

- winch side arms to reinforce truck frame
- bronze-bushed, 4-way cable guide rollers
- cable drum guard
- heavy-duty pipe bumper
- needle-bearing, universal-joint spline-shaft drive assembly
- Timken bearings on worm

King Winches keep you moving through the most difficult terrain . . . you get action where there's no traction with dependable pulling power. King power winches have pulling capacities of 8,000 to 19,000 lbs.

* *King Winches for International trucks are available through International-Harvester dealers.*

Koenig ALL-STEEL CABS FOR JEEPS

FULL AND HALF CABS

Koenig Jeep cabs and King Winches for Willys vehicles are available through Willys Motors, Inc., and Willys-Overland Export Corp. distributors or dealers. Write for free descriptive literature.

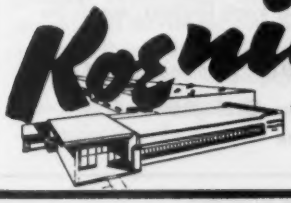
Full Cab and Model 151J King Winch Illustrated.

KOENIG ALL-STEEL CABS HAVE THESE SUPERIOR FEATURES:

- PROTECTION
- SAFETY
- COMFORT
- CONVENIENCE

Roll-down windows, full opening . . . full panel-board head lining and masonite door lining . . . safety glass throughout . . . all-steel welded construction . . . door locks.

Koenig



IRON WORKS, Inc.

P. O. BOX 7726 HOUSTON 7, TEXAS

Now Available!

HABITAT of OIL

A Symposium; INCLUDING PAPERS PRESENTED AT THE FORTIETH ANNUAL MEETING OF THE ASSOCIATION, AT NEW YORK, MARCH 28-31, 1955, AND SOME ADDITIONAL PAPERS

Analytically reviewed and edited by

LEWIS G. WEEKS

Published by the Association, 1958

OUTLINE OF CONTENTS

General Review—Analysis of facts, interpretations, principles and theories presented in the symposium.

North America—Oil occurrences in Los Angeles Basin, Cuyama and San Joaquin Valleys, California; Alberta and Williston basins, Canada; Williston basin, northern Great Plains, and Rocky Mountains; Powder River, Big Horn, Wind River, Denver, Uinta, and San Juan basins; Permian basin, West Texas-New Mexico; Michigan, Illinois, and Appalachian basins; Eastern Gulf Coast. Tectonics of southern Mexico . . . 20 papers.

South America—Oil occurrences in southern Trinidad, Eastern Venezuela, and Maracaibo basins; Middle Magdalena Valley, Colombia; La Brea-Pariñas field, Peru . . . 5 papers.

Topical Papers—Facies control of oil accumulation; source rocks; kerogen; hydrocarbons and oil migration in Recent sediments; hydrocarbons in subsurface waters; basin mechanics and habitat of oil . . . 9 papers.

Modern Basins—Recent sediments and ancient rocks; basins off southern California; organic matter in sediments of Lake Maracaibo; Black Sea; Gulf of Mexico . . . 5 papers.

Europe—Oil occurrences in northwest Germany; northeastern Netherlands; Aquitanian Basin, France; Rhine graben; Vienna Basin; Po basin; eastern slope of Russian platform . . . 7 papers.

Middle East—Oil occurrences in northern Iraq; Kuwait-Basra area; southwest Iran; Saudi Arabia . . . 5 papers.

Far East—Oil occurrences in northwestern Borneo; East Borneo; south Sumatra; East Java . . . 4 papers.

56 articles 1364 pages Index Cloth To members $9.00; Non-members $11.00

The American Association of Petroleum Geologists
Box 979, Tulsa 1, Oklahoma

No matter where your oil prospects may be . . .

chances are General Geophysical Company has experience in the area (but not on the moon, *yet*) General's experienced crews and their modern field equipment have headquarters in seven division offices, and are accessible to nearly every oil area on the globe. This broad geographical coverage means faster, better coordinated geophysical service for you. And, regardless of where they are located, the services performed by General Geophysical crews set the standards of the exploration field.

General's division headquarters (▲) and supervisory field offices (●) are located in or near most of the free world's oil active areas.

General

GEOPHYSICAL COMPANY

HOUSTON CLUB BUILDING • HOUSTON, TEXAS

In Canada: 10509 81st Avenue, Edmonton, Alberta, Canada

General Geophysical Company de France (SARL), 4 Square Rapp • Paris 7, France

General Geophysical Company de Venezuela, C. A., Sociedad A. Camejo No. 55 • Caracas, Venezuela

General Geophysical Company (Bahamas) Ltd.

WHEN YOUR CONTRACT IS WITH GENERAL, THE PERCENTAGE FOR SUCCESSFUL EXPLORATION IS IN YOUR FAVOR

A progress report—

Glen Canyon Dam Project to open vast new area

Work on huge Upper Colorado River Project well under way

When completed some six years hence, the giant Glen Canyon Dam, Reservoir and Powerplant Project will unlock the riches of a vast, 10,000-square-mile area.

The high concrete gravity arch dam, rising 700 feet from bed-rock, will contain 5,493,000 cubic yards of concrete. Power from the 900,000 KW power plant, located 470' downstream from the dam, will make possible the development of huge resources of fuel, oil, minerals—including uranium—and timber.

When filled to capacity the 28,000,000-acre-foot reservoir will stretch 186 miles up the Colorado and 71 miles up the San Juan, a major tributary of the Colorado. Basically, this project is for river control and power generation.

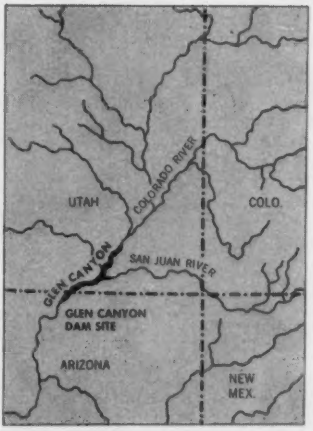
Largest single dam contract on record

The $107,155,222 contract for the Glen Canyon Dam and Powerplant, largest ever awarded by the U.S. Bureau of Reclamation, went to Merritt-Chapman & Scott Corporation, New York. On April 29, 1957, the day the contract was awarded, Merritt-Chapman & Scott signed a contract with Fairchild for aerial mapping of the dam site, reservoir and areas adjacent to the dam site. Flying operations began on May 5, *just six days later!* Advance copies of flying results were delivered on May 26. Other detailed data followed soon after.

Scale of maps for Glen Canyon

Reservoir: 1" equals 400', 10' contours
Dam site: 1" equals 50', 2' contours
Areas adjacent to dam site: 1" equals 200', 5' contours

During the past 34 years, Fairchild crews have flown similar mapping assignments all over the free world. Results produced from this experience have led thousands of Fairchild clients to say... if you want it done *fast* and *right the first time*, you can depend on Fairchild.



Site of the 700' Glen Canyon Dam, second in height only to Hoover Dam (726') is located 12 miles downstream from the Arizona-Utah border—370 miles upstream from Hoover Dam.

Walls of the canyon at the dam site are 650' high with overhang in places. This necessitated flight paths parallel to the walls but offset to see under the overhangs.

FAIRCHILD AERIAL SURVEYS, INC.

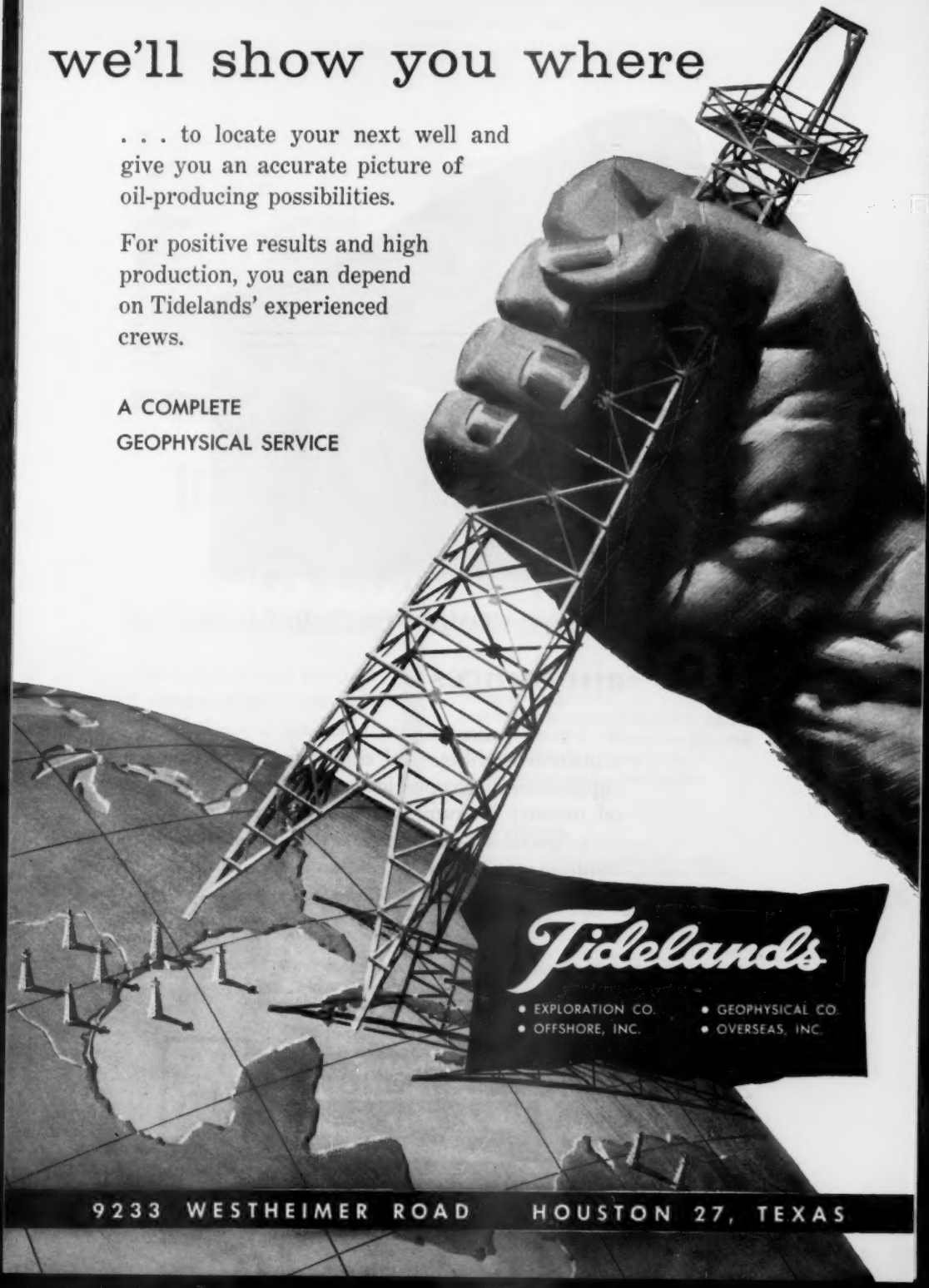
Los Angeles, California: 224 East Eleventh Street • **New York, New York:** 30 Rockefeller Plaza • **Chicago, Illinois:** 111 West Washington • **Long Island City, New York:** 21-21 Forty-First Avenue • **Tallahassee, Florida:** 1514 South Monroe Street • **Boston, Massachusetts:** New England Survey Service, 255 Atlantic Avenue • **Shelton, Washington:** Box 274, Route 1 • **Houston, Texas:** 3325 Las Palmas • **Birmingham, Alabama:** 2229 First Ave. North

we'll show you where

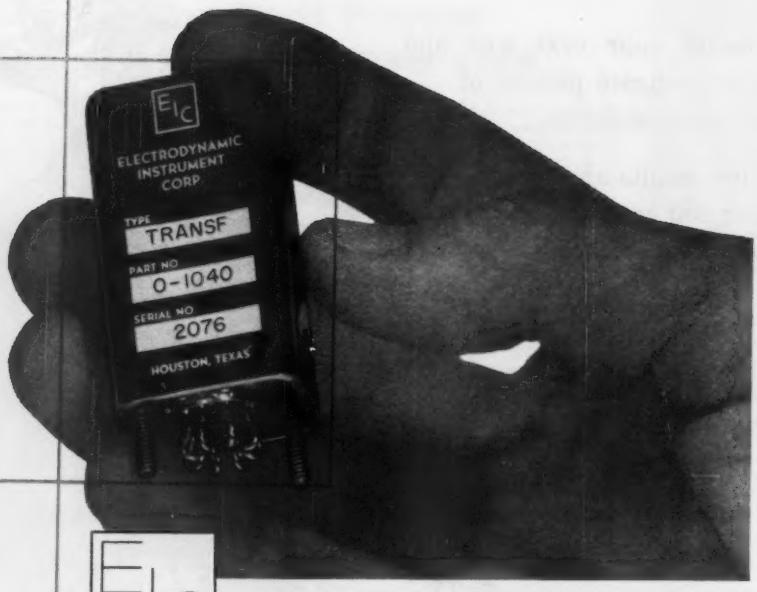
. . . to locate your next well and give you an accurate picture of oil-producing possibilities.

For positive results and high production, you can depend on Tidelands' experienced crews.

A COMPLETE
GEOPHYSICAL SERVICE



9233 WESTHEIMER ROAD HOUSTON 27, TEXAS



WOUND COMPONENTS DEPT.

announces

its line of precision transformers, filters and chokes for low frequency applications in geophysical and other oil industry instrumentation.

Special custom designs also are available. Your inquiries are invited.

ELECTRODYNAMIC
INSTRUMENT
CORPORATION

2508 Tangley Road
Houston 5, Texas

TRANSISTOR POWER SUPPLY
MODEL 523-500A PAT. APPL. FOR
INPUT TERMINALS + 2 - 1
27 VDC 2.4 AMPS
OUTPUT TERMINALS + 5 - 4
150 V .2 A Regulated
OUTPUT TERMINALS + 4 - 3
150 V .1 A Regulated
SN: 1 MAX. CASE TEMP 74°C
ARNOLD MAGNETICS CORP. LOS ANGELES, CAL.

transistorized voltage supply for seismic amplifiers

Here is a *completely static* unit which is far more dependable than vibrators or dynamotors. The ARNOLD power supply is used as a regulated supply for vacuum tube or transistorized seismic amplifiers. Inherent in the design and construction are these advantages:

No radiated interference
No ripple below 1KC
Low output impedance from 0 to 1KC
Shock resistant and **hermetically sealed**
Operates from −65°F to +160°F
No moving parts—hence long life and no maintenance.

SPECIFICATIONS
Input: 6, 12 or 24 volt batteries.
Output: Any voltage from 6 to 1200 volts, regulated 2% for discharging battery and variations of load, simultaneously.
Weight: 19 ounces.
Size: 3" diameter x 3 3/16" high.

Arnold power supplies are used by Pan American Petroleum Corp., Seismic Explorations, Inc., and other leading companies. *Write for literature on the Model 591-E.*

ARNOLD MAGNETICS CORP.
4613 West Jefferson Boulevard, Los Angeles 16, California
Telephone REpublic 1-6344

BERT & RALPH DUESING

"Selling Atlas Explosives"

BIG LAKE, TEXAS — HASKELL, TEXAS

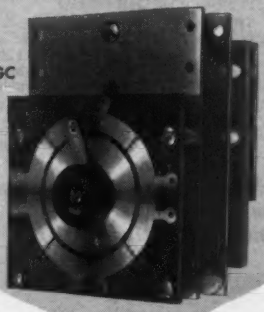
HIGH ALTITUDE

Balloon

CONTROL INSTRUMENTS

require MAXIMUM *Performance—*
MINIMUM *Size—Weight—Power Drain*

Model AGC



ENGINEERING DEVELOPMENT MANUFACTURING
SUB FRACTIONAL WATT D.C MOTORS BRAILSFORD SIGNALLING SYSTEM COMPONENT

Brailsford AGC Timers Are Unmatched in These Basic Requirements

If you have a timing problem where size, mass, and power drain are critical, read these

SPECIFICATIONS
Model AGC

Number of decks—1-4

Speed regulation—±1.0% at 50% voltage shift

Size—1¾" x 2¼"—depth depends on number of decks

Segments per deck—2-8 for stock units. Special commutators to order for a nominal tool charge.

Shorting or non-shorting contact

Power input—.008 Amp. at 6 VDC

Write for literature

BRAILSFORD
and Company, Inc.
670 Milton Road
Rye, N.Y.

MAYES-BEVAN
GRAVITY METER
M
B
SEISMOGRAPH
COMPANY

KENNEDY BUILDING • TULSA, OKLAHOMA

EUROPEAN ASSOCIATION
OF
EXPLORATION GEOPHYSICISTS

The E.A.E.G. was founded in December 1951

The aims of the Association are to promote the science of exploration geophysics by establishing contacts and encouraging co-operation and fellowship between geophysicists in Europe and elsewhere and by disseminating knowledge of the science through the agency of regular meetings and the publication of technical papers.

MEMBERSHIP

Active Members pay an annual membership fee of Neth. fls. 15.—, increased by Neth. fls. 0.50 collecting charges. In U.S. currency this charge amounts to $4.10.

Prospective Members. Anybody interested in geophysics can apply for membership by sending in an Application Form, duly filled out. Forms will gladly be supplied by the Secretary-Treasurer of the E.A.E.G. but may also be obtained through the kind assistance of the Business Manager of the S.E.G.

GEOPHYSICAL PROSPECTING

Official Journal of the European Association of Exploration Geophysicists

This journal is issued quarterly and contains articles written in English, French or German. English, however, is predominant and each article is preceded by an abstract in that language.

Active members receive the journal free of charge.

In accordance with the Terms of Affiliation with the Society of Exploration Geophysicists, members of that Society may enter a current subscription to the journal for the normal membership fee.

The Subscription Rate for non-members is Neth. fls. 22.—(U.S. $5.80) per annum. Single copies are available at Neth. fls. 6.—(U.S. $1.60). These rates include packing and postage and are payable in advance. A limited quantity of previous issues is still available at the same price.

Advertising rates will be sent upon request.

All communications to be directed to:

THE SECRETARY-TREASURER E.A.E.G.

30, C. VAN BYLANDTLAAN • THE HAGUE • NETHERLANDS

HERE and ABROAD

THE

RED WEIGHT

IS

GEOGRAPH

Searching for OIL

FIRST IN THE FIELD OF WEIGHT DROPPING

In Canada, Algeria, all over the world, McCollum GEOGRAPH crews are proving the weight drop technique's speed, safety, economy and accuracy in the search for oil. The versatility of GEOGRAPH in hard rock areas, frozen terrain, desert sand, etc., illustrates its advantages over conventional methods in obtaining accurate seismic data while completely eliminating the need for shot holes and explosives. Seventeen years of research and development on GEOGRAPH assures the world market the most effective and economical exploration method.

McCOLLUM SINCE 1923
Exploration Company
1025 S. Shepherd Drive, JAckson 8-5427, Houston, Texas

VIP*

VARIABLE INTENSITY PLOTTER

Most rapid and economic means for time-correcting and compressing seismic data in section form!

The VARIABLE INTENSITY PLOTTER developed by Texas Instruments rapidly corrects for time or depth and compresses a mass of seismic data into section form, while preserving the relative character and contrast of recorded events. The VIP cross section closely approaches a geologic section, and is therefore readily comprehended by non-geophysical personnel.

VIP is the first *all-electronic* system devised for variable density presentations, with the added speed, reliability and accuracy which this assures. Further distinct advantages of the VARIABLE INTENSITY PLOTTER are:

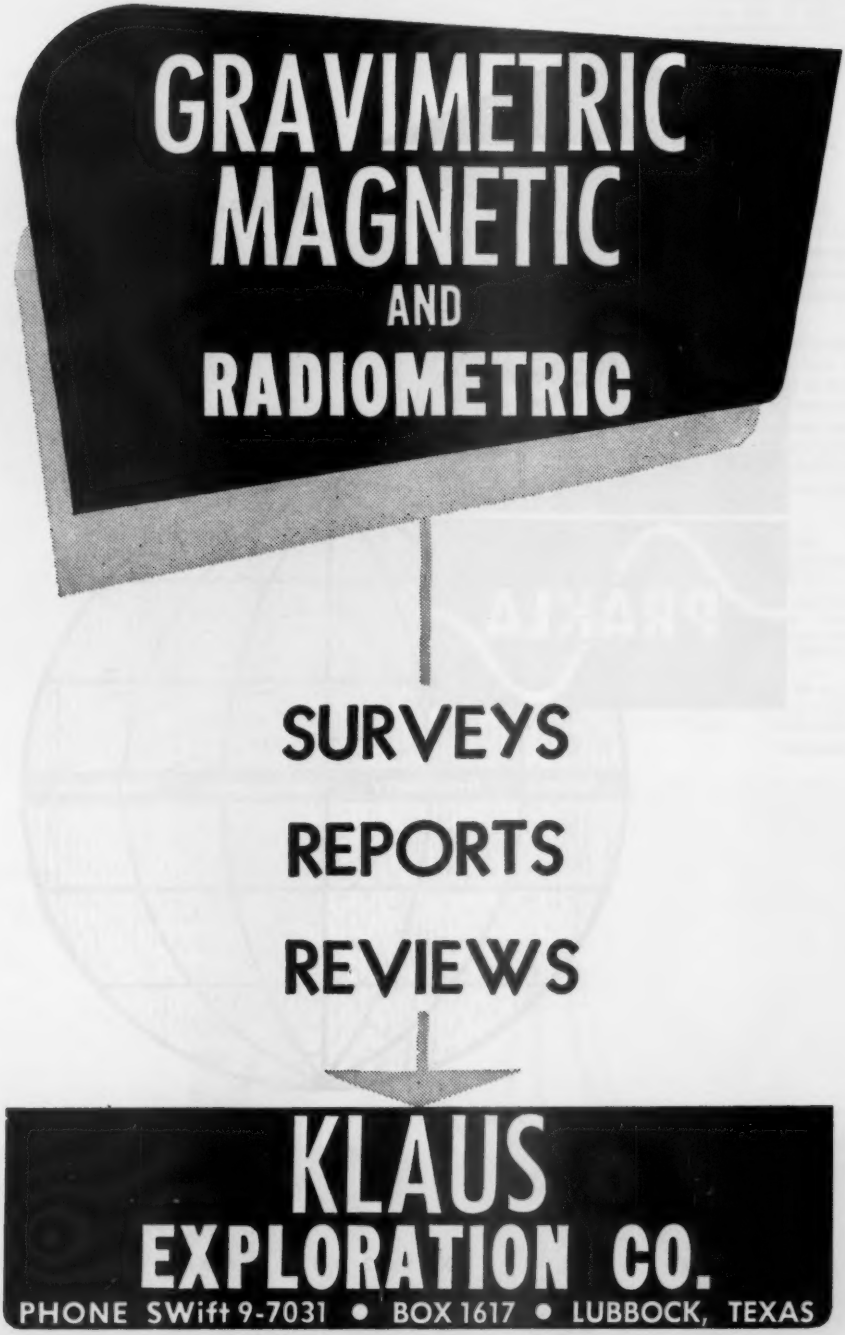
1. Low initial cost—lowest processing cost per profile.
2. Operates directly from magnetic recording—no intermediate record.
3. Usable with all magnetic transducers.
4. 24 time-corrected channels simultaneously processed in one minute.
5. Inherent information retained independently of trace width.
6. Timing accuracy of ± 1 millisecond.
7. Visual examination of data on 20-inch cathode ray tube.
8. Photographic record on 2¼" x 3¼" negatives with obvious storage advantages.
9. Traces can be mixed.
10. Monitoring of all data possible prior to and during processing.
11. Visual indication of time and depth scale on record.
12. Easily transported—can be operated by semi-skilled personnel.

Write today for complete information, specify Bulletin No. S-322.

TEXAS INSTRUMENTS
INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

a Seismation system

*TRADEMARK REGISTRATION APPLIED FOR.


GRAVIMETRIC
MAGNETIC
AND
RADIOMETRIC
SURVEYS
REPORTS
REVIEWS
KLAUS
EXPLORATION CO.
PHONE SWift 9-7031 • BOX 1617 • LUBBOCK, TEXAS

HANNOVER · HAARSTRASSE 5

PHONE: 8 66 61 · TELEX: 922 847 · CABLE: PRAKLA

CYANAMID

MADE-TO-ORDER TREMORS!

Earth tremors made to your order . . . and a perfectly-timed record every time —are two of the specific advantages you will find in Cyanamid's specialized, high-quality line of seismograph explosives!

On-shore or off-shore, Cyanamid's years of experience and complete line of quality explosives are at hand to help you solve any exploration problem you may come up against. Accurate and profitable exploration start with QUALITY explosives—CYANAMID Explosives! For more information, just call CYANAMID.

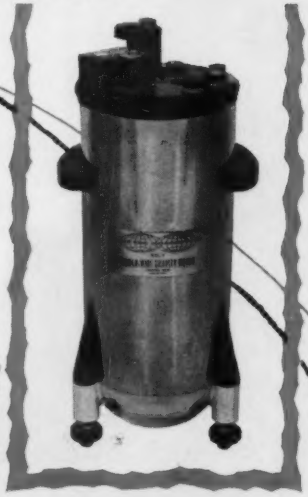
AMERICAN CYANAMID COMPANY
Explosives and Mining Chemicals Department
30 Rockefeller Plaza, New York 20, N. Y.

DISTRICT SALES: St. Louis, Missouri · New York City, New York · Latrobe, Pennsylvania · Pottsville, Pennsylvania · Scranton, Pennsylvania Dallas, Texas · Salt Lake City, Utah · Bluefield, West Virginia

THE CYANAMID SEISMOGRAPH LINE:* Hi-Speed Geogel · Ajax S · Pattern Powder—Available with Fast Coupler or E-Z Lok · Blasting Agents —Cyamon OS

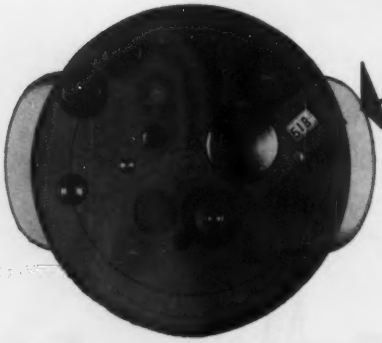
*Trademark

the new
IMPROVED DESIGN
that sets a new standard in GRAVITY METERS



WORLD-WIDE EXCLUSIVE FEATURES

- **EASY READING COUNTER** enables the operator to read the meter without removing from the tripod.
- **RECESSED LEVEL BUBBLE** avoids direct sunlight thereby eliminating level bubble creep.
- **WORLD-WIDE RANGE** for all meters regardless of latitude, without returning to laboratory for further range adjustments.
- **SMALL DIAL RANGE** of approximately 100 milligals minimizes resetting instrument in rugged terrain.

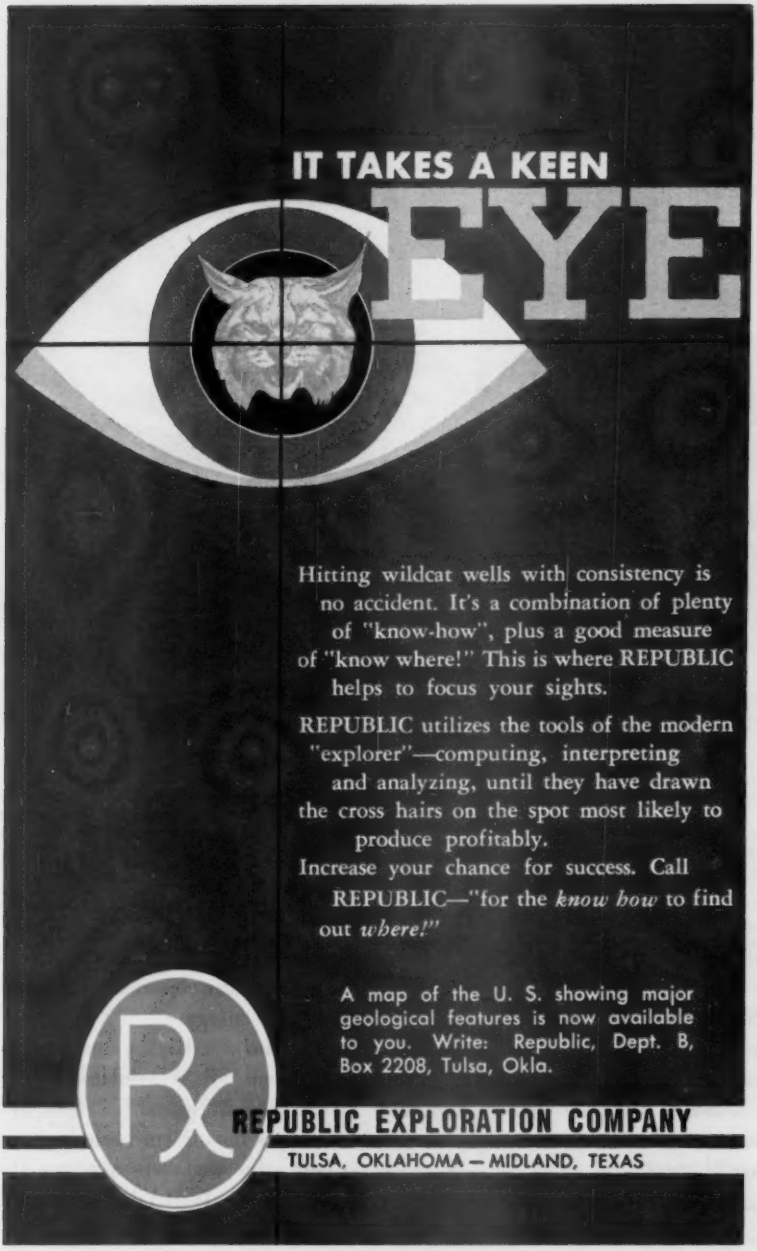


- Lightweight, completely portable
- .01 milligal reading accuracy
- Thoroughly temperature compensated
- Direct digital reader
- No external power source required
- Full two year warranty

- Direct reading digital counter facing upwards, and read like an automobile mileage recorder, enables operator to read without removing from tripod. Small dial range approximately 100 milligals.

WORLD WIDE INSTRUMENTS, INC.

3802 South Shepherd—Houston 6, Texas U.S.A.
Cable Address: WRLDWIDINS HOUSTON


IT TAKES A KEEN
EYE
Hitting wildcat wells with consistency is no accident. It's a combination of plenty of "know-how", plus a good measure of "know where!" This is where REPUBLIC helps to focus your sights.
REPUBLIC utilizes the tools of the modern "explorer"—computing, interpreting and analyzing, until they have drawn the cross hairs on the spot most likely to produce profitably.
Increase your chance for success. Call REPUBLIC—"for the know how to find out where!"
A map of the U. S. showing major geological features is now available to you. Write: Republic, Dept. B, Box 2208, Tulsa, Okla.
Rx
REPUBLIC EXPLORATION COMPANY
TULSA, OKLAHOMA — MIDLAND, TEXAS

The NEW VIBROCAP® SR for PATTERN SHOOTING

Hercules' continuous program of research and development has provided a new Vibrocap SR. This new Vibrocap SR gives seismic blasting crews an improved electric blasting cap for land, marsh, and offshore exploration. The new cap features:

Improved . . . Series firing for pattern shooting with faster, more uniform firing at lower current with high voltage blasters.

Improved . . . Regularity of firing at both high and low currents.

Improved . . . High resistance to accidental di charge by static electricity, stray currents, and rad frequency energy.

Improved . . . High water resistance.

Vibrocap SR is available with plastic-insulate kirked wires in regular packages, or on spools packe in cartons having convenient carrying handles.

Our sales engineers welcome the opportunity tell you more about Vibrocap SR and to consult wi you on blasting procedures.

HERCULES

HERCULES POWDER COMPANY

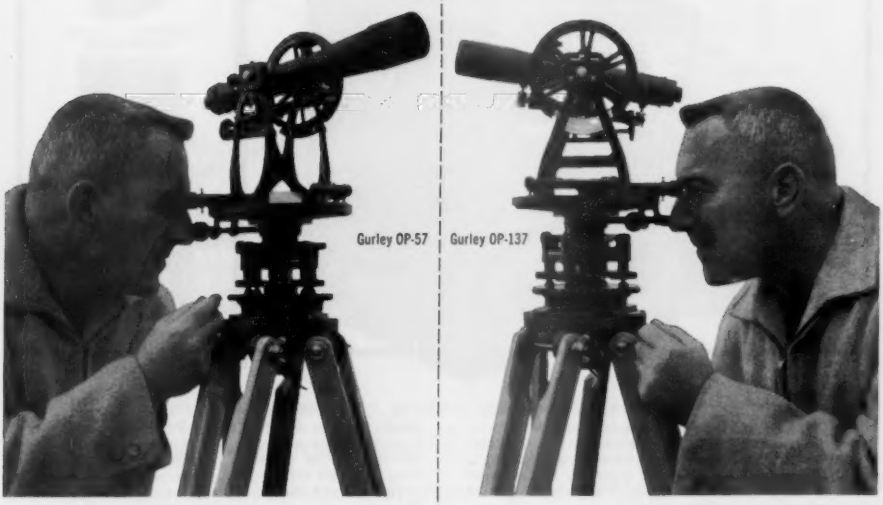
INCORPORATED

Explosives Department · 900 Market St., Wilmington 99, Del.

XR57-

Birmingham, Ala.; Chicago, Ill.; Duluth, Minn.; Hazleton, Pa.; Joplin, Mo.; Los Angeles Calif.; New York, N. Y.; Pittsburgh, Pa.; Salt Lake City, Utah; San Francisco, Calif

Built-in optical plummets eliminate plumb bobs save set-up time...improve accuracy



The Gurley Optical Plummet Transit (Model OP-57) has proved itself to be such an important time and money saver in the field that this optical plummet feature has also been added to the Model 132 Standard Precise Transit. The new transit will be known as the OP-137.

Both these Optical Plummet Transits will save you time and trouble in setting over a point. The OP-57 and OP-137 eliminate the swing and sway of the cord and plummet—exasperating and time consuming. You will especially appreciate the increased accuracy on windy locations.

By rotating the instrument 180°, you can be assured of positive centering.

The Gurley Optical Plummet Transits are furnished with tripods which have built-in shifting heads. They allow a two-inch shift of instrument over the point, providing greater latitude in initial set-up.

Model OP-57 is recommended for very exacting work; the OP-137 for general engineering and construction work because of its shorter telescope, smaller size and its lighter weight.

Now in *two* models Gurley offers you an important advantage of the optical-reading theodolite *plus* the simplicity, ruggedness and proved performance of the American transit. *Write for new Bulletin OP-100.*

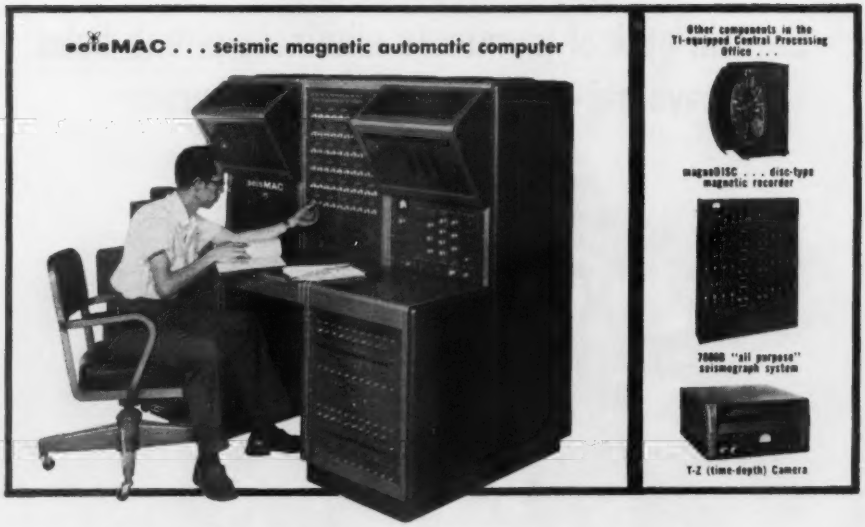
W. & L. E. Gurley
Engineering Instruments Division
Troy, New York
Since 1845

GURLEY

W. & L. E. Gurley, Engineering Instruments Division
529 Fulton St., Troy, N. Y.
Please send new bulletin OP-100 with details on Gurley's Optical Plummet Transits.

NAME
TITLE
ORGANIZATION
ADDRESS
CITY ZONE NO. STATE

TI | seisMAC* brings new speed . . . accuracy . . . flexibility to seismic data processing!


seisMAC . . . seismic magnetic automatic computer
Other components in the TI-equipped Central Processing Office . . .
magneDISC . . . disc-type magnetic recorder
7000B "all purpose" seismograph system
T-Z (time-depth) Camera

The seisMAC, seismic magnetic automatic computer, developed by Texas Instruments Incorporated, is an analog data reduction machine controlled by a digital programmer. seisMAC provides for constant (weathering and elevation) and variable (normal moveout) corrections to be made to any number of seismic traces played back from the magneDISC or other magnetic recorder.

seisMAC, in conjunction with the other individual blocks used in the TI Central Processing Office (or a mixture of equipments, if desired), makes possible the preparation of either time or depth record sections with all the original character of seismic data preserved and the presentation enhanced. Some of the outstanding advantages of seisMAC which permit the presentation of data in its most comprehensible form for final interpretation by the geologist-geophysicist team are:

1. Constant and variable time corrections are made automatically.
2. Unlimited repeatability of data within one millisecond accuracy.
3. Provides 100 millisecond constant plus 100 millisecond variable corrections with no frequency, phase or amplitude distortion.
4. Adaptable with most magnetic transports.
5. Completely automatic during the processing — no adjustments need be made during the operation cycle.
6. No moving heads or cams to become misaligned — seisMAC is the first all-electronic system.
7. Immediate adaptability to any spread or velocity change.
8. Each trace is time-corrected sequentially and independently — no proportioning of a single NMO function for correcting inner traces.
9. Signal remains in analog form with digital programming — high speed processing, accuracy, and repeatability are inherent in the system.

For more complete information on the seisMAC and the TI-equipped Central Processing Office, write for Bulletin No. ___S-318.

*TRADEMARK REGISTRATION APPLIED FOR

TEXAS INSTRUMENTS INCORPORATED
INDUSTRIAL INSTRUMENTATION DIVISION
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB
Formerly: HOUSTON TECHNICAL LABORATORIES
Seismation®

7246

FOR SHALLOW AND DEEP LOGGING USE...

ELECTRIC LOGS (S.P. & RES) (recorded simultaneously)	GAMMA RAY-CASING COLLAR LOGS (recorded simultaneously)
GAMMA RAY-RESISTANCE LOGS (recorded simultaneously)	GAMMA RAY LOGS

featuring—

- **Exclusive automatic dry process photographic recording unit**
- **Electric powered cable hoist**
- **"Turn-key" package with generator and all accessories**
- **High strength armored steel logging cable**
- **Interchangeable components — one GEO-LOGGER does all**
- **Compactness — Simplicity — Reliability — Durability**
- **Proven design — over 8 years' acceptance in the field**

FOR REAL ECONOMY IN SHALLOW LOGGING USE THE NEW SHOT HOLE Geo-Logger

Ideal for shot hole and shallow core hole logging to 750 feet. Has all the features of the famous SHALLOW and DEEP units, including electric generator and all accessories. Easily operated by any member of a drilling or seismic crew without special training.

SHOT HOLE
SHALLOW
DEEP
Geo-Logger packaged units are ready for delivery and immediate use, on a monthly lease or purchase basis. For information, contact

WELL RECONNAISSANCE, INC.

7818 Brook Hollow Road • Box 1483 • Dallas, Texas • TELEPHONE: FLeetwood 7-7378

manufacturers of the finest portable logger — approved throughout the world

Please mention GEOPHYSICS when answering advertisers

Field party on survey for proposed Canyon Dam on Texas' Guadalupe River.

TYPE FA-176

W&T SURVEYING ALTIMETERS SPEED HYDROLOGIC STUDY OF RESERVOIR BASIN

A ground-water and geologic survey, involving water table isograms for 400 square miles adjoining the proposed Canyon Dam Reservoir on Texas' Guadalupe River, recently was completed in 35 days. Despite difficult terrain and maximum relief of 1000 feet, over three hundred spot elevations were taken during this period. The speed with which this work was done is attributed to the use of the two-base method of altimetry employing three Wallace & Tiernan Type FA-176 Surveying Altimeters.

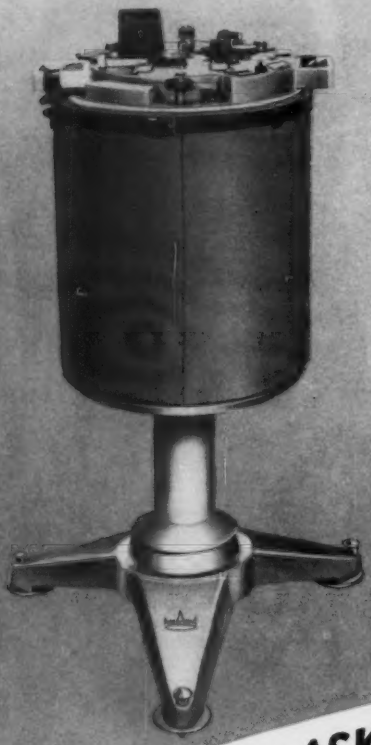
Technical data on the FA-176 Altimeter include: **Range** — any interval of 2000′ up to max. limit of 5000′; **Accuracy** — 2.0′; **Sensitivity** — 0.5′; **Scale Length** — 20″; **Dial Size** — 8½″ dia.

For details on FA-176, send for Bulletin No. TP-7-A

WALLACE & TIERNAN INCORPORATED

25 MAIN STREET, BELLEVILLE 9, NEW JERSEY

In Canada, Wallace & Tiernan, Ltd. — Toronto A-117.43



GRAVIMETER Gs 12

is an instrument of the type Gs 11, which additionally is equipped with a set of calibrated weights. By these weights (i.e. 19 balls) a difference in gravity of about 2,000 mgals can be compensated and measured. This can be done for any multiple of 100 mgals directly. Intermediate values are determined as before by means of a fine measuring spring.

ASKANIA

NEWEST ASKANIA INSTRUMENTS

TORSION MAGNETOMETER Gfz

is a new Askania-Magnetometer of high quality. Here are the data:

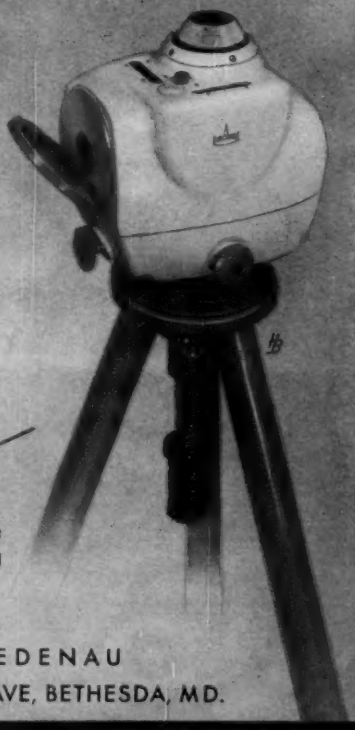
Range:	65,000 γ
Sensitiveness:	25 γ / s. d.
Reading accuracy:	≤ 0.1 s. d.
Weight:	3 kg (6.6 lb.)

Temperature compensated and independent of the azimuth.

Tripod for rough and final levelling.

And the result of all these advantages:

One measurement takes 40 seconds only!



Write for detailed specifications and additional information on these latest developments and on other Geophysical Instruments for Prospecting and Scientific Research.

ASKANIA-WERKE AG · BERLIN-FRIEDENAU

U.S. BRANCH: ASKANIA-WERKE AG · 4913 CORDELL AVE, BETHESDA, MD.

DALLAS
MAYHEW
TEXAS

MODEL
200-T

featuring maximum application versatility . . .

SHOOTING UNIT

Transports explosives, shooting equipment, and water for shot-tamping in seismic operations. Includes racks for loading poles, casing or drill stem.

SHOT-HOLE DRILL

Light-weight rotary type utilizing chain pulldown, double-drum drawworks, 4½ x 5 mud pump. Pump provides uphole water velocity of 300 ft. per minute with a 4" bit.

WATER TANK

All-steel body incorporates water tank, racks to carry drill stem, loading poles, or casing.

TRACTOR-MOUNTED

to permit year-round operations in most areas formerly inaccessible to truck-mounted equipment.

★ Choice of International 350 or Ford 820 tractor. Half-tracks optional.

HOME OFFICE

MAYHEW SUPPLY CO., INC.

4700 SCYENE ROAD • DALLAS, TEXAS

SALES AND SERVICE

CASPER, WYOMING • TULSA, OKLAHOMA • SIDNEY, MONTANA • LUBBOCK, TEXAS • GRAND JUNCTION, COLORADO • GALLUP, NEW MEXICO • EXPLORATION EQUIPMENT CO., INC., HOUSTON, TEXAS

CANADA

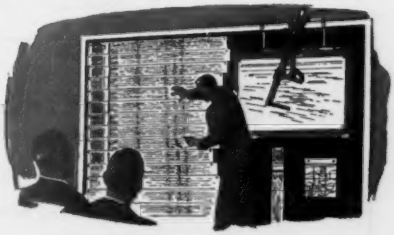
SEISMIC SERVICE SUPPLY, LTD., CALGARY AND EDMONTON, ALBERTA

EXPORT

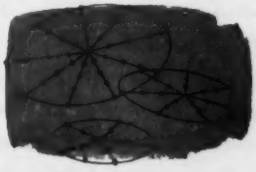
EXCO — HEADQUARTERS: DALLAS, TEXAS, P. O. BOX 1330

SEI

EXPERIENCE



INTERPRETATION



TECHNIQUE

For twenty-six years, SEI has specialized in subsurface studies of the domestic oil provinces . . . from Canada to the Gulf. Numerous innovations in instrumentation, interpretation, and field technique have kept SEI in the forefront. For example, in difficult areas, SEI has been a pioneer in the use of patterns of multiple shot holes and geophone arrays.

Your exploration program is in capable hands at SEI.

SEISMIC EXPLORATIONS INCORPORATED

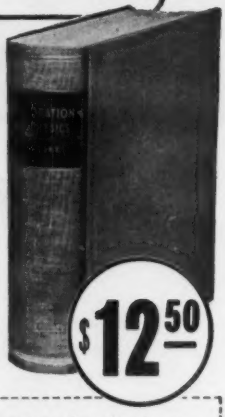
1017 SOUTH SHEPHERD • HOUSTON, TEXAS

Area Offices: Midland, Texas • Shreveport, Louisiana • Oklahoma City, Oklahoma • Billings, Montana

An easily read, clearly illustrated text on
Modern Geophysical Techniques

EXPLORATION GEOPHYSICS

by J. J. Jakosky, Sc. D.



In more than 1200 pages and with 715 illustrations, the 1957 revised printing of *Exploration Geophysics* covers the entire field of exploration by modern geophysical methods. It is concisely and clearly written by an internationally known geophysicist, in close collaboration with 39 other leading authorities.

Thirteen fact-packed chapters fully cover all contemporary methods; plus permit, trespass and insurance problems. A basic textbook for every geologist, geophysicist, engineer and physicist concerned with exploration well logging and production Adopted by many leading universities.

$12.50

FREE EXAMINATION

Send your money order or check for $12.50 for a copy of Exploration Geophysics on 5-day approval. If you are not fully satisfied, merely return the book in its original condition and your money will be promptly refunded.

TRIJA PUBLISHING COMPANY, 2502 W. COAST HIGHWAY, NEWPORT BEACH, CALIFORNIA

RESEARCH GEOPHYSICIST

To conduct original research, both theoretical and experimental, in problems of elastic wave propagation and related data processing techniques. Ph.D. or equivalent in physics, geophysics, or related field. Strong background in mathematical physics required. Experience in exploration seismology research helpful, but not required. Salary open. Our staff is aware of this advertisement.

Send complete resume to Department G, Box 1536, Tulsa 1, Oklahoma.

ZEITSCHRIFT FÜR GEOPHYSIK

Ed. by Deutsche Geophysikalische Gesellschaft

Editor: B. Brockamp

This periodical publishes original contributions in German, English, and French which have not previously appeared in Germany or elsewhere, as well as general surveys in all branches of pure and applied geophysics. It is the official journal of the Deutsche Geophysikalische Gesellschaft and keeps geophysicists in Germany and abroad in touch with current results of scientific research. Applied geophysics is allotted wide coverage without neglecting other branches of geophysics and related fields.—Six issues a year.

We will send you a specimen copy upon request.

PHYSICA-VERLAG
WÜRZBURG 2 / GERMANY

In longitudes East and West, in latitudes North and South . . . on each of the six continents . . . Robert H. Ray crews are at work. During every minute of the day, somewhere RHR men are busy recording, computing, and interpreting geophysical data. These many and varied man hours create direct and efficient methods . . . produce detailed and accurate results.

Expertly manned and completely equipped for either Seismic (Reflection and Refraction), Magnetometer, or Gravity methods, Robert H. Ray Co. is prepared to carry your explorations to any geographical location.

This vast experience is cumulative. It works for *You* in every contract with Robert H. Ray Co.

ROBERT H. RAY CO.

2500 Bolsover Road • Houston 5, Texas

RHR CO · SEISMIC · MAGNETIC · GRAVITY

ROBERT H. RAY **ROBERT S. DUTY JR.** **JACK C. POLLARD** **NORMAN P. TEAGUE**

TEX-TUBE

SHOT HOLE CASING 16 GAGE - 19 GAGE With The EXCLUSIVE SPEED COUPLER JOINT

Strong, and light-weight **Tex-Tube** Shot Hole Casing with the exclusive Speed Coupler Joint will solve your shot hole problems! Light enough to carry in—strong enough to drill with! Each length of 16 gage **Tex-Tube** Shot Hole Casing weighs only 20 pounds. Each length of 19 gage weighs 13 pounds. The exclusive **Tex-Tube** Speed Coupler Joint makes up fast—without collars. Only two quick turns make a water tight connection strong enough for high pressure jetting. Field tests prove **Tex-Tube** best.

H & T Sales Co.	Beeville, Texas	FLeetwood 8-1642
Bilderback Dynamite Co.	Lafayette, Louisiana	CEnter 4-6184
	Houma, Louisiana	UPtown 2-0861
Par-Tain Exploration Co.	Bakersfield, California	FAirview 5-3764
Deupree Distributing Co.	Oklahoma City, Oklahoma	JAckson 8-6740
Grove Hardware Co.	Oklahoma City, Oklahoma	JAckson 8-4886
Teton Tool Co.	Mills, Wyoming	CAsper 2-7181
Seismic Service Supply, Ltd.	Calgary, Alberta, Canada	5-5691
Venezuelan Supply, C. A.	Caracas, Venezuela	71-53-21
National Supply Co. Export Division	New York City	Circle 6-3232

Tex-Tube, Inc.

Houston, Texas
UN 9-3411

Baton Rouge, Louisiana
ELgin 5-1430

Houma, Louisiana
UPtown 2-0569

Planning Exploration or Mapping?

Invite the 3 million mile man

He's been in 52 countries . . . knows the problems and the pitfalls. He's the AERO engineer, representing the pioneer and leader in aerial surveys.

AERO crews are at work now in the great desert areas and mountain fastness of the Middle East, putting thousands of uncharted square miles on the map. They have mapped ten million acres of Guatemalan jungle, defining oil concessions there. They have mapped several thousand miles of the proposed new highway routes right here in America. This kind of staff can bring to any large scale mapping or exploration job an efficiency resulting from more than three million miles of world-wide aerial survey experience.

Whether you need photo-geological studies, precise topographic maps or magnetic studies, let the AERO 3-million mile man show your planning group how modern AERO methods save time, money and manpower.

AERO SERVICE CORPORATION

PHILADELPHIA 20, PENNSYLVANIA

Oldest Flying Corporation in the World

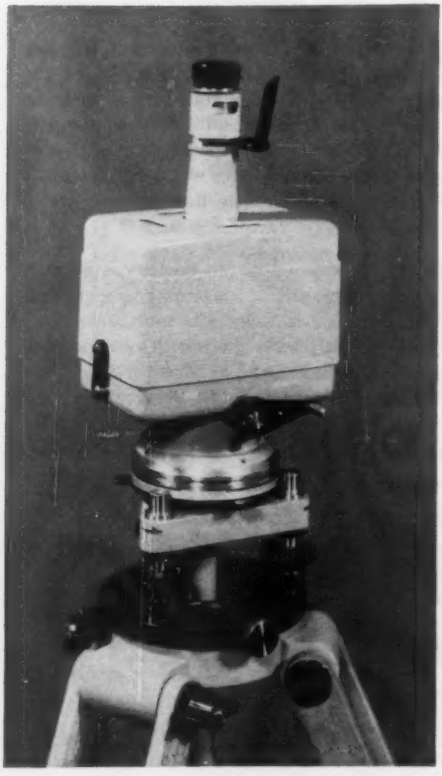
Offices in: TULSA, SALT LAKE CITY, SAN FRANCISCO, JOHANNESBURG, LONDON, CARACAS

Our Canadian affiliate is:
CANADIAN AERO SERVICE LIMITED, OTTAWA

PRECISE AERIAL MOSAICS
TOPOGRAPHIC MAPS
PLANIMETRIC MAPS
AIRBORNE MAGNETOMETER SURVEYS
SCINTILLATION COUNTER SURVEYS
ELECTROMAGNETIC DETECTOR SURVEYS
GEOPHYSICAL INTERPRETATION
RELIEF MODELS

RUSKA MAGNETOMETERS

Now with New Type Temperature Shielding



TYPE V—Vertical Magnetic Field Balance

TYPE H—Horizontal Magnetic Field Balance

TYPE VR—Vertical Magnetic Recording Balance

TYPE HR—Horizontal Magnetic Recording Balance

Standard Sensitivity
10 gamma per scale division —visual

10 gamma per millimeter— recorded

"SCOUT"—a light-weight vertical reconnaissance magnetometer

Standard Sensitivity
25 gamma per scale division

All Ruska magnetometers are equipped with temperature compensated systems with sapphire knife-edges.

ALSO: HOTCHKISS TYPE SUPER-DIP

BETTER BECAUSE THEY ARE MADE TO BE BETTER

A superior product plus a program of continual improvement keeps Ruska instruments unsurpassed. Built to remain accurate and to stand hard use, they are the choice of prospectors the world over.

RUSKA INSTRUMENT CORPORATION

4607 MONTROSE BLVD. HOUSTON 6, TEXAS

MAKE A STRIKE

WITH

Milligal

With the proven, accurate, dependable interpretations of our GRAVITY SURVEYS, you are more apt to make a strike. Get the benefits of prompt, precise geophysical service through the application of our latest proven scientific methods.

E. V. McCollum Craig Ferris

515 Thompson Bldg. Phone CHerry 2-3149

Tulsa, Oklahoma

E.V.McCOLLUM & CO.

WE WEIGH THE EARTH

Foreign Affiliate: NAMCO INTERNATIONAL

Electro-Tech Gravity Meters

(FORMERLY MANUFACTURED BY NORTH AMERICAN GEOPHYSICAL CO.)

Accurate Control of Temperature Guarantees Lowest Drift-Rate

Electro-Tech Portable Gravity Meters are manufactured in several models, each specially designed for particular applications. Sensitivities and accuracies of 0.01 milligal are provided on all meters except for tidal recording use where one microgal sensitivity and accuracy is usual. No barometric or temperature corrections are necessary.

LAND GRAVIMETERS AG-1 standard exploration model has reading range of approximately 100 milligals. Quick reset mechanism allows use in any latitude or elevation.

MARSH GRAVIMETERS Remote controlled RM-1 is unequalled for work in shallow water, mud or swamp areas. Small movements of operator, boat or vehicle do not disturb readings.

ELECTRO-TECH

RENT OR RENTAL PURCHASE

ELECTRO-TECHNICAL LABS

Division of Mandrel Industries, Inc.

P. O. Box 13243 Houston 19, Texas

SEISMOGRAPH SURVEYS*

*long and short term contracts

C. N. PAGE A. E. "SANDY" McKAY C. J. LOMAX

Central Office
2111 Continental Life Bldg.
Fort Worth, Texas

Division Offices

WEST TEXAS
Midland, Texas

GULF COAST
Houston, Texas

ROCKY MTS.
Denver, Colorado

Foreign Affiliate: namco INTERNATIONAL

A MAJOR ADVANCE!

A TRULY PORTABLE MAGNETOMETER

FOR GEOLOGICAL AND GEOPHYSICAL EXPLORATION

THE VARIAN M-49

operating on revolutionary nuclear-free-precession principle detects variations in the earth's magnetic field associated with magnetic ore bodies, subsurface faults and structural anomalies. Sensitivity of plus or minus 10 gammas is more than ample for the purpose. An extremely short (6 second) automatic reading interval permits rapid reconnaissance of large areas. Weight is only 16 pounds.

The Varian M-49 needs no leveling, calibration or orientation in azimuth. Its readings are precise even when the magnetometer is in motion — carried by a man on foot — mounted on horseback — or embarked in a boat. The sensing head is connected by cable and can be separated from the instrument body by several hundred feet—suspended by balloon—lowered over vertical cliffs.

To achieve these unique properties, Varian uses the proton free-precession principle which relies on an immutable nuclear constant (of the hydrogen atom). Other Varian magnetometers operating on this same principle are in use in magnetic observatories, airborne surveys, underwater surveys and in space vehicles.

FEATURES...

- Range 19,000 to 100,000 gammas.
- Direct reading meter in gammas; sensitivity of ± 10 gammas; no calibration required.
- Weighs only 16 pounds; all-transistor design; compact and rugged.
- Reading interval manually controlled or six-second automatic; usable stationary or in motion.
- Cable-connected sensing head separable by several hundred feet for multilevel surveys.
- Polarizing cells rechargeable by simple connection to automobile battery.

Write today for a full explanation of the Varian Magnetometer's principles, applications and equipment details.

VARIAN associates

INSTRUMENT DIVISION

611 Hansen Way, Palo Alto 23, California

EXPERIENCE

IN ALL PARTS OF THE WORLD IX crews boast an excess of 330 crew years of combined experience in 24 of the United States, and 75 crew years of geophysical exploration in 15 foreign countries with all sorts of terrains and in conditions ranging from sub-arctic to tropic. No matter where your contemplated explorations are, IX has a crew standing by in your vicinity. For the best possible data anywhere in the world, call on IX.

OVER 1763 MAN YEARS OF EXPERIENCE

INDEPENDENT EXPLORATION CO.

Geophysical Surveys

1973 West Gray, Houston, Texas 3 Frederick's Place, Old Jewry, London, E.C.2, England 12 Rue Chabanais, Paris, France 103 Rue Michelet, Algiers, Algeria

The

GEOPHYSICAL DIRECTORY

for 1958

Just Off The Press

A Comprehensive Directory for the Entire Geophysical Industry

●

COMPLETELY REVISED and improved. Covers U.S., CANADA and FOREIGN AREAS.

Lists OIL COMPANIES using geophysics, GEOPHYSICAL CONTRACTORS, and SUPPLIERS, PERSONNEL LIST of more than 3500 names.

$4.00 per copy

●

Order your copy today from

THE GEOPHYSICAL DIRECTORY
P.O. Box 13176
HOUSTON 19, TEXAS

WHAT FRIENDS OF 26 YEARS AGO SERVE YOU TODAY ?

Let's roll back the calendar to 1932

Snowy northwestern Oklahoma... an operation by Sinclair... one of Petty's long-standing clients. Since then many others have joined the growing list of customers who, like Sinclair, rely on Petty year after year. Today, Petty personnel use the most modern methods as they build records of continuous service for a host of successful companies. May we show you specifically how Petty has found lasting friends by helping them in their search for oil.

1932

1958

33 YEARS EXPLORATION IN ALL TERRAIN

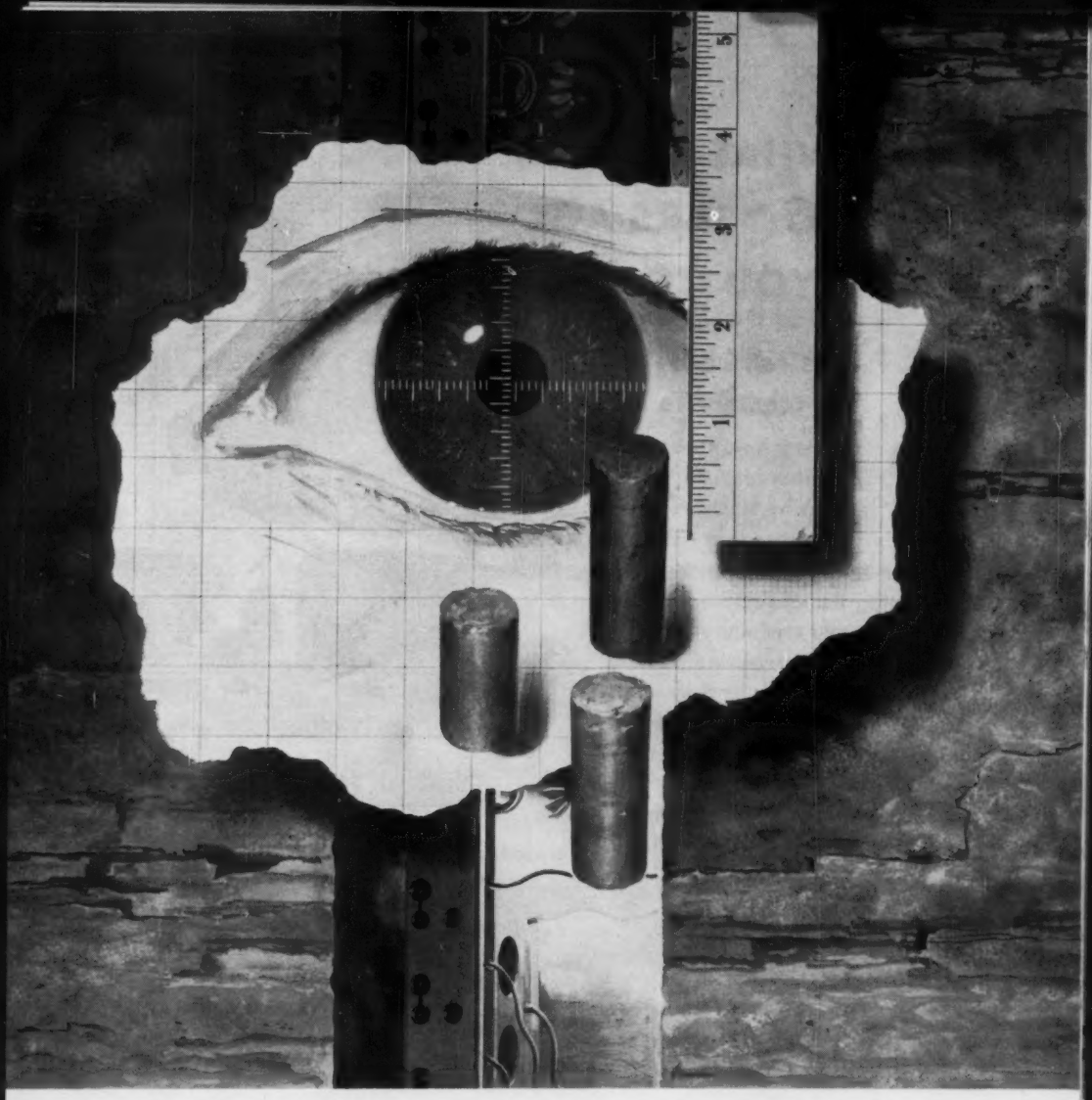
Petty

GEOPHYSICAL ENGINEERING CO.

SAN ANTONIO 8, TEXAS

DISTRICT OFFICES: Houston, Tulsa, Denver, Lafayette

Seismic Gravity Magnetic Surveys



It "threads the needle" at any depth

In hard or soft formations, successful side-wall coring operations can be performed with the Schlumberger Side-Wall Coring Instrument. Up to 30 cores (large enough for a complete core analysis) can be obtained on one trip in the hole.

Pin-point accuracy is assured since cores are obtained at exactly the desired depth by using the S.P. Curve as a direct reference.

The Schlumberger Side-Wall Coring Instrument is simple, it's safe, it's proved by thousands of runs to be fast and dependable. Also to your advantage, a Schlumberger coring operation costs much less than conventional, wire line or diamond cores taken at the same depths.

Ask your Schlumberger representative to advise you how Schlumberger Side-Wall Cores can help reduce costs, and give a better, faster look at production possibilities.

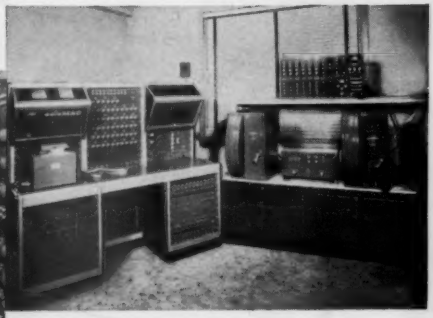
THE EYES OF THE OIL INDUSTRY®

SCHLUMBERGER

T/I

magneDISC*

DISC-TYPE MAGNETIC RECORDER



Best in the Field!

The magneDISC has proved its operational superiority in exacting seismic data recording conditions throughout the world.

Greater Capacity—Record up to 115 data and auxiliary traces at one time.

Reliable and Rugged—No pampering required . . . no air-conditioned, dust-free, humidity-controlled environment is needed for accurate performance of the magneDISC.

No "Barber-Poling"—The disc is the most stable geometric design for magnetic recording . . . no skewing of tape to affect accuracy.

Recording Heads stay in precise alignment—discs can be played interchangeably on any magneDISC—tolerances are maintained to insure timing accuracy of ±½ millisecond trace to trace.

Best in the Central Processing Office!

The versatility of the magneDISC is unsurpassed in the CPO, used in conjunction with the seisMAC for automatic data reduction.

Speed of Processing—utilizing two 115 head magneDISC Transducer Units, data may be played from one through the seisMAC and re-recorded on the other in one continuous operation.

Greater Operational Latitude—two T/D Units provide 230 channels of information for mixing, compositing, or stacking as desired—no necessity for synchronization of several drums as with other systems.

Easier Handling and Storage—one movement of lever accurately positions disc in the T/D Unit—eject button pushes disc out for easy removal. magneDISCS take up less storage space than any other type of magnetic recording medium.

For complete information and the many other advantages of the magneDISC, write for Bulletin ___S-307; or request a visit from the TI representative!

TEXAS INSTRUMENTS INCORPORATED

INDUSTRIAL INSTRUMENTATION DIVISION

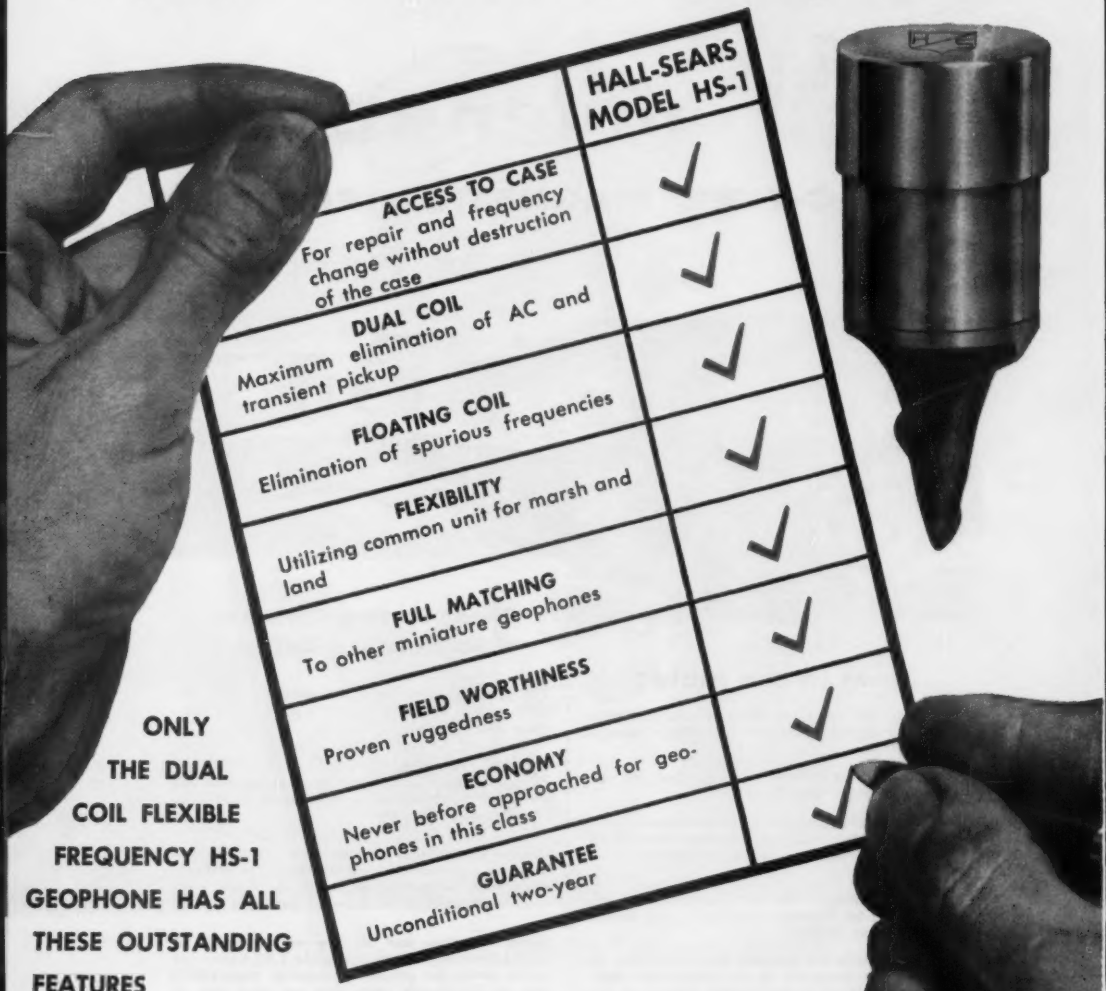
3609 BUFFALO SPEEDWAY • HOUSTON, TEXAS • CABLE: HOULAB

Formerly: HOUSTON TECHNICAL LABORATORIES

* a Geosource system

7090

CHECK THESE POINTS WHEN PLANNING YOUR NEEDS



	HALL-SEARS MODEL HS-1
ACCESS TO CASE For repair and frequency change without destruction of the case	✓
DUAL COIL Maximum elimination of AC and transient pickup	✓
FLOATING COIL Elimination of spurious frequencies	✓
FLEXIBILITY Utilizing common unit for marsh and land	✓
FULL MATCHING To other miniature geophones	✓
FIELD WORTHINESS Proven ruggedness	✓
ECONOMY Never before approached for geophones in this class	✓
GUARANTEE Unconditional two-year	✓

ONLY THE DUAL COIL FLEXIBLE FREQUENCY HS-1 GEOPHONE HAS ALL THESE OUTSTANDING FEATURES

THE HS-1 MEETS THE NEEDS FOR IMPROVED GEOPHONES

Rental and rental-purchase plans also available

HALL-SEARS, INC.

2424 BRANARD STREET • HOUSTON 6, TEXAS • CABLE—ELTEC

European Headquarters: 2 BANSTRAAT — HALL-SEARS EUROPA, N.V. THE HAGUE, HOLLAND — CABLE: EUROTEC

Portable housing...for foreign use...in 15 minutes at ½ the cost

LIGHTWEIGHT "D" SERIES

- Available 8 x 8, 10 x 10, 10 x 20
- Aluminum frame
- Convas roof and curtains
- Aluminum screen
- Plywood floor

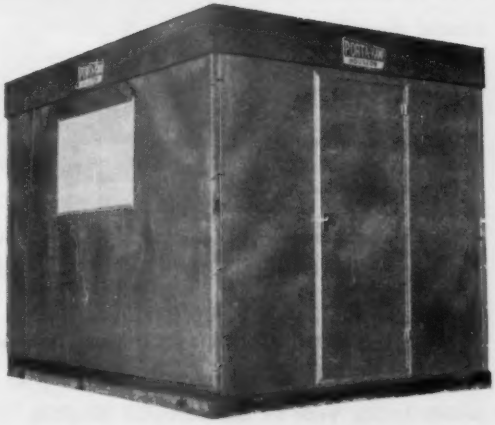
Model D-1-C Shown

- Size 10′ x 10′
- Weight 550 lbs.
- Collapsed size 14″ x 41″ x 120″ Ready for shipping

HEAVY DUTY "K" SERIES

- Fully insulated
- All aluminum exterior
- Assemble 15 minutes
- Join 2 or more together

Also — complete line of tents and tarps



MODEL K-10 SHOWN

- Size 8′ x 10′ x 7½′
- Weight 850 lbs.
- Collapsed size: 8′ x 10′ x 13″

PORTA-KAMP HOUSTON

716 W. 16 HOUSTON, TEXAS

a major break-through in GEOPHYSICAL EXPLORATION METHODS

Ten years of research in methods of electrical prospecting has resulted in the development of AFMAG, a revolutionary geophysical tool. Employing only natural magnetic fields of audio and sub-audio frequencies as a source of energy, AFMAG provides many advantages when applied to the search for conductive mineral deposits.

- Elimination of line cutting
- Extraordinary depth of exploration
- One man operation
- Quick, accurate surveys under any topographic conditions
- Direct interpretation of results in the field
- Complete conductivity analysis of conductive bodies
- Minimizes response of swamps and surface clay beds

AFMAG is unquestionably the most significant development in recent years to be made available for mining exploration. For full data on the principle and its proven results, write for our illustrated brochure.

CROSSLAND LICENSING CORPORATION LIMITED

OFFICE 15 — OFFICE MEZZANINE

The King Edward Sheraton Hotel, Toronto

William A. Robinson, B.A.Sc.
President

S. H. Ward, Ph.D.
Executive Vice President

Rogers crews go everywhere . . . .

If your proposed petroleum province lies along the Po, or on the Pampas; if it's in the states or the Sahara . . . Rogers crews are there now (or have been). For these are the crews that operate worldwide, that assure you accurate geophysical surveys.

Consult Rogers about your potential province, regardless of its location.

Rogers *Geophysical Companies*

3616 WEST ALABAMA • HOUSTON, TEXAS

Edificio Republica • Caracas, Venezuela
Mogadiscio • Somalia
34 Ave. des Champs Elysees • Paris, France
1-3 Arlington St., St. James's • London S.W. 1, England

Geophysics abroad

Ask SEISMOS GmbH HANNOVER-GERMANY

Central Processing Office with seisMAC system

equipped to process
HTL Magnetic Discs
SIE Magnetic Tapes

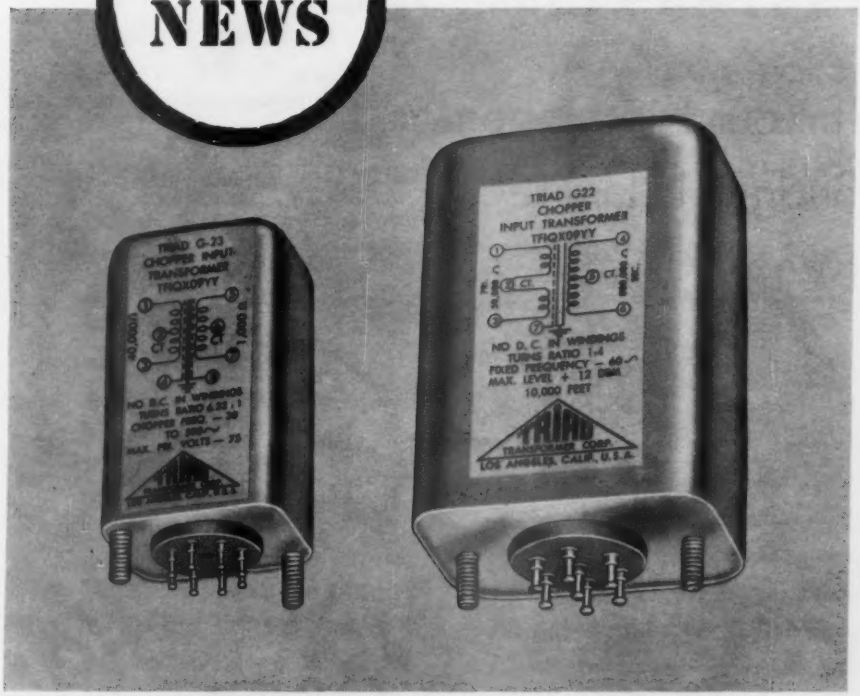
Geophysikalische Messungen überall

SEISMOS GmbH HANNOVER

Refraktion · Reflexion · Gravimetrie (zu Lande und zu Wasser)
Geoelektrik (Eigenpotential · Widerstand · Induktion)
Szintillometrie (carborne)
Magnetik

Please mention GEOPHYSICS when answering advertisers

TRANSFORMER NEWS FROM TRIAD



GEOPHYSICAL TRANSFORMER RELIABILITY

Every coil on every Triad Geophysical Transformer is tested (1) before impregnation, (2) before assembly, and (3) after completion. Induction tolerances are held within ±5% of standard. In addition to the Triad Geophysical Transformers listed in our catalog (all especially designed to meet the peculiar and difficult conditions of geophysical prospecting) we will supply units to *your* specifications—at reasonable cost and in reasonable time.

These are some of the reasons why Triad Geophysical Transformers have long been the standards of excellence for geophysical prospecting. We'll gladly send you our catalog. Please ask for **TR-58.**

TRIAD

4055 REDWOOD AVENUE, VENICE, CALIFORNIA
812 E. STATE STREET, HUNTINGTON, INDIANA

A SUBSIDIARY OF LITTON INDUSTRIES

Please mention GEOPHYSICS when answering advertisers

If Your Exploration Budget Is Limited, Read This

The use of the gravity meter as a means to get the most from a seismic program has been recognized for many years. Nevertheless, when exploration budgets are large, there is a tendency to put on more and more seismic crews, rather than go through the reconnaissance phase of selecting the most favorable places for them to work. But when the dollars are limited, too few seismic crews not favorably placed may be adding to the exploration manager's problems.

If you do not have as many seismic crews as you would like to have, a small percentage of the budget invested in gravity work, to guide the activities of your few precious crews, could make the difference between success and failure.

Gravity meter surveys are inexpensive compared with seismic. Their cost runs in the vicinity of 3 cents an acre. The use of this tool to guide further exploration that may cost 30 or more times as much is indicated by the economics alone.

Through the years we have emphasized this use of gravity work and we will be pleased to discuss its application to your exploration program.

Thomas J. Bevan
910 South Boston

Ed M. Handley
Tulsa, Oklahoma

Please mention GEOPHYSICS when answering advertisers

He couldn't make gold from Lead

But-

The **SSC SEISVERTER**

can make
new seismograms
from old

NOW, YOU CAN HAVE FULLY CORRECTED CONVENTIONAL OR VARIABLE DENSITY CROSS SECTIONS FROM OLD FIELD SEISMOGRAMS

SSC's new Seisverter automatically converts old seismograms into modern, fully corrected magnetic or photographic seismic records. These records may be produced in either conventional or variable density form.

The new instrument will handle original record speeds of 9 to 17 inches per second.

Contact SSC today for Catalog Sheet B-44, which contains complete information on the new Seisverter.

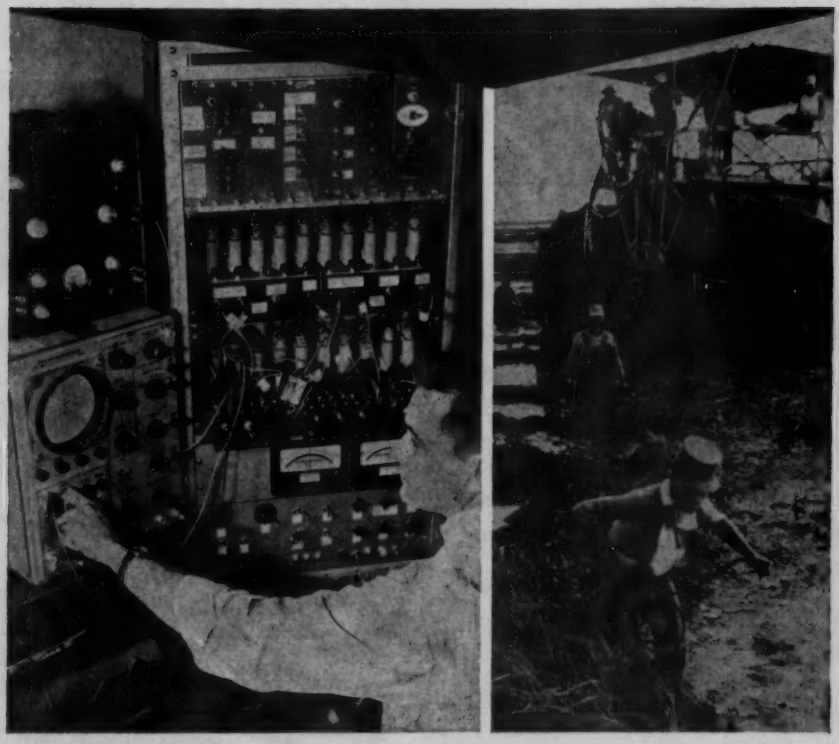
SEISMIC — GRAVITY AND MAGNETIC SURVEYS — LORAC — CONTINUOUS VELOCITY LOGGING

Seismograph Service Corporation

6200 East 41st Street • TULSA, OKLAHOMA • Riverside 3-1381

WORLD-WIDE SUBSIDIARIES

SSC of Canada • SSC of Colombia • SSC of Bolivia • SSC of Libya • SSC of Nigeria
SSC of Venezuela • SSC International
Seismograph Service Limited — England
Seismograph Service Italiana • Compagnie Francaise de Prospection Sismique



lab or field, **these** men revise the textbooks*

Do your potential reserves wait in "no record" areas? Are they obscurely trapped in areas of easy shooting? Do ghost reflections or singing records cause you to miss important discoveries? GSI's *problem-solving* staff welcomes such difficulties.

. . . Yesterday's textbook solutions no longer provide all the right answers. Where classical techniques are inadequate, GSI revises the text.

We supplement active field experience with research, experimentation, imaginative thinking—a total approach to geophysics. Our aim: To help you find more oil, within the limits of profitable exploration.

GEOPHYSICAL SERVICE INC.
100 EXCHANGE PARK NORTH • DALLAS 35, TEXAS

*GSI... continuing leadership through research and growth